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ORIENTATION OF SYNTHETIC CORUNDUM FOR JEWEL BEARINGS[1]

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ABSTRACT

By a method similar to that used in petrofabric analyses, a correlation between crystallographic boule orientation and processing results is shown for synthetic corundum made in America by the well-known Verneuil process. For best processing results, the growth axis of a synthetic corundum boule should lie approximately normal to a second order pyramid face with indices $\{11\bar{2}2\}$. A second favorable orientation is close to $\{81\bar{9}0\}$. Boules grown normal to various faces in the zone of negative rhombohedrons generally show irregular to hackly fracture when split, and yield definitely inferior results in jewel-bearing manufacture. Economic savings could be effected if boule manufacturers would control the orientation of their product.

INTRODUCTION

Jewel bearings have long been used in fine watches and instruments to reduce friction on small pivots or axles which must turn easily if the instrument is to function properly. Such bearings usually take one of several shapes depending upon the purpose and service to which they are put. The simplest consists of a polished conical depression terminated at the apex by a spherical surface on which the pivot rides as shown in Fig. 1 at *A* and *E*. This is called a vee jewel. Wear resistance and durability in vibration and shock have been related to the position of the crystallographic *c*-axis in such jewels by several writers. Stott (1931, p. 54) states that the angle between a vee-jewel axis and the crystallographic *c*-axis should be over 30°, and probably less than 80°. Goss (1941, p. 814) prefers this angle to be between 80° and 90°. Grodzinski (1942, p. 167) states it should be either 45° to 48° or 60° to 90°. No exhaustive research has ever been published regarding wearing properties and orientation of the other types of jewel bearings, which are described below. A simple jewel bearing is shown in Fig. 1 at *B*. It consists of a flat plate of jewel material with one side polished, and with a polished cylindrical hole normal to the polished side. It is called a bar hole jewel. The hole serves to hold the pivot in place with respect to lateral stresses, and the polished flat surface serves as a thrust-bearing, as shown at *F* in the figure. Although simplest in design and use, the vee-jewel and the bar hole jewel have certain objectionable mechanical features that make two additional jewels useful at especially critical points, as in the escapement and balance wheel assembly of a fine watch or chronometer. These jewels are illustrated at *C* and *D* in the figure; they are called the olive hole jewel *C* and the endstone jewel *D*. The olive hole jewel is a more or less flat plate with a toric hole so shaped that the pivot can theoretically touch it only along a line of contact. This jewel is not suitable for sustaining end thrust and therefore the endstone jewel is provided as a complementary part, presenting a polished flat or convex surface against which the spherically-shaped polished end of the steel pivot rotates with a minimum of contact area. The relations of these two jewels and a pivot are shown at *G* in the figure.

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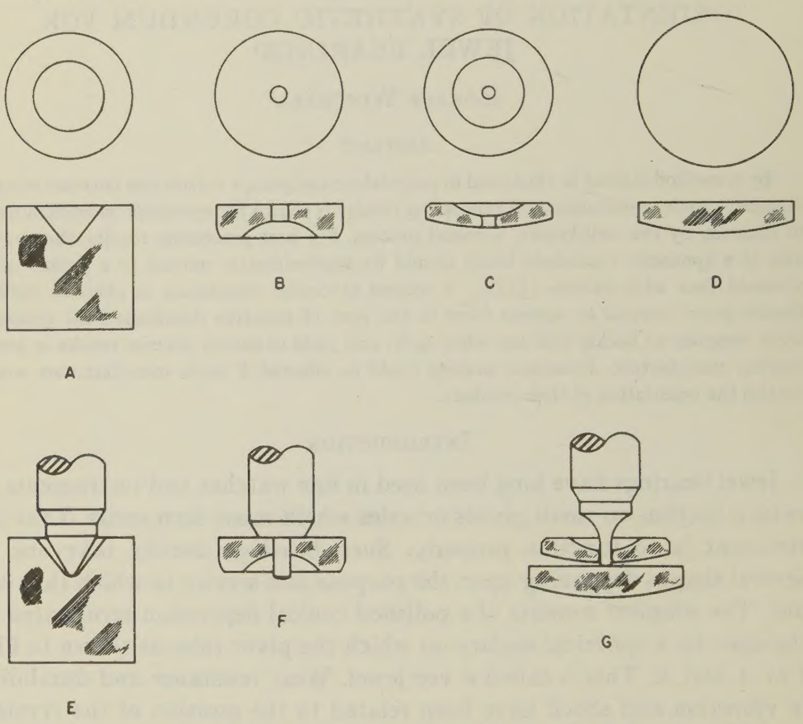

FIG. 1. Four recognized types of jewel bearings. *A*, Vee jewel; *B*, Bar hole jewel; *C*, Olive hole jewel; *D*, Endstone jewel; *E*, Assembly showing vee jewel and pivot; *F*, Bar hole jewel and pivot; *G*, Olive hole jewel, endstone jewel, and pivot.

JEWEL MATERIALS

Conventionally, the above-described jewel bearings are made from hard materials, either crystalline or vitreous; the commonest and most satisfactory material is synthetic corundum made by the Verneuil process which need not be described here. The raw material for jewels comes from the Verneuil furnace as a roughly cylindrical, homogeneous, gem-quality crystal or boule whose surface has no definite relation either in shape or in orientation to the lattice of the crystal of which it is composed. In synthetic corundum boules there are stresses which can be relieved only by breaking the boule. Boules of good quality invariably break lengthwise with a smooth, approximately plane fracture which will here be called the parting plane. Figure 2 shows several boules lying on their parting planes, and one in end view showing the shape after splitting. Experience shows that the parting plane is always that plane which contains both the growth axis (length) of the boule and the *c*-axis of the crystal. The angle between these axes may have any value whatever from 0° to 90°, although boules in which this angle is less than about 30° tend to be inferior. Because of the uniaxial character of corundum crystals, it is easy to measure this angle in polarized light; but it is impossible to determine by polarized light the relation between the parting plane or the growth axis and the minor crystallographic axes, a_1, a_2, a_3.

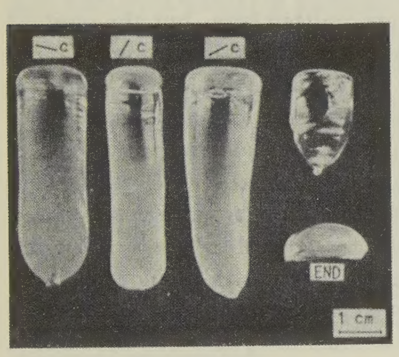

FIG. 2. American synthetic white corundum boules. The orientation of the *c*-axis is indicated above the three large boules. The small boule is an early specimen made before the technique reached its present efficiency. End view of a split boule.

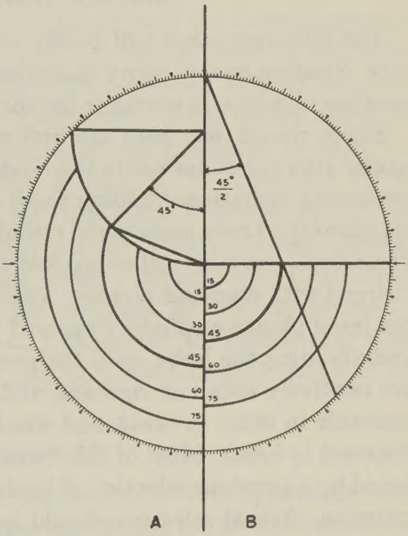

FIG. 3. Comparison and graphical construction of equal area (*A*) and stereographic (*B*) projections.

By x-ray diffraction methods it may be proved that there is no fixed relation between the orientation of the parting plane or the growth axis and that of the minor axes, although the parting plane must of course always lie in, or close to, the prism zone. Statistically, however, the parting plane is more often approximately parallel to a prism face of the first order, or to one of the second order, than to any other prism face; this may be deduced from the data to be given below.

MANUFACTURING PROCEDURE

The following steps will briefly outline the process of jewel manufacture. Needless to say, many operations are omitted here, but the omitted ones are of minor importance for the purposes of this discussion.

Small, round, flat discs are first cut from the boules. These discs are nearly always cut normal to the boule axis by three mutually perpendicular sawing operations yielding small squares. The squares are surfaced to standard thickness, and ground round in a centerless grinder. The resulting "roundels" are next drilled by fine wire drills rotating at high speed and charged with diamond powder. The holes are opened to size by stringing the jewel blanks on slightly tapered wires charged with diamond powder and abrading the holes until the proper size is reached. The above steps are relatively rough or vigorous, and it is sometimes assumed that this is desirable in order to break and eliminate any material that may be predisposed to break. Most of this "weak" material could probably be eliminated by a previous selection of boules, based on orientation as a primary criterion. Actual selection should be based upon more easily measured characters if possible. The finishing steps in jewel manufacture involve concentric grinding and various polishing and shaping operations to produce oil-holding depressions around the holes, lens-shaped surfaces instead of flat ones, polished surfaces, etc. Most of these steps are gentle, and spoilage due to broken jewels is relatively low in the finishing processes.

DEVELOPMENT OF AMERICAN INDUSTRY

When the war brought to an end the previous Swiss supply of jewel bearings for instruments and watches, the United Nations were temporarily hindered by a lack of jewels. It was necessary to develop quickly a source of synthetic corundum boules and a jewel making industry to fabricate them. Several American suppliers have developed boule manufacture to such a point that there is now very little danger that we might experience any shortage of synthetic corundum, The jewel-bearing industry has now attained a mass production basis in this country, so that the worst part of the jewel shortage is probably over. Partly on account of unfamiliar processing methods and partly on account of variable raw material, considerable loss was experienced at first, through waste of material, breakage, and other factors. It was therefore necessary to improve the mechanical processes of jewel production and also to study the jewel material itself to determine if it could be classified according to any scheme which might improve production efficiency. The latter studies constitute the subject of this paper.

ACKNOWLEDGMENTS

This research was carried out with the facilities of the Crystallographic and Abrasives Research Laboratory, and with the cooperation and facilities of various production departments of the Hamilton Watch Company, of Lancaster, Pennsylvania, whose sponsorship is gratefully acknowledged. I am indebted to many employees of the Company for their cooperation, but special mention is due Messrs. R. W. Mentzer, H. D. Weaver, J. O. LeVan, and R. Potts, for their aid in following special lots of jewels and jewel blanks through various production channels. Special thanks are due Mr. G. E. Shubrooks, Chief Chemist and Metallurgist, for many helpful suggestions and for criticism of the manuscript. I sincerely thank my colleague, Miss C. I. Neetzow, for painstaking work in analyzing many *x*-ray patterns and in preparation of many of the diagrams reproduced.

THE ARGUMENT

The fundamental thesis of this discussion is the hypothesis that crystallographic orientation is an important aspect of the fabrication and use of all tools and products made from crystalline materials, and especially from single crystals of any material. This thesis has been argued by Kraus and Slawson (1939; 1941) for the special case of diamond. Hamilton experience has fully confirmed their general hypothesis in that case.

This hypothesis implies that boules having orientation "*X*" will in general give different results both in fabrication of jewels and in wearing ability of the product, when compared with boules having orientation "*Y*." Heretofore, it has been tacitly assumed that the differences, if any, are negligible; or that if not negligible, such differences are impracticable to determine. A simple criterion has been found for determining, at least approximately, the distinction between two important orientation-types of boules. This criterion enables one to predict with a fair degree of confidence, whether a given boule will be easily and efficiently processed, or will give more-than-average broken pieces (and less efficiency) in processing.

ORIENTATION STUDIES

There is only one criterion which can be used for separating boules into two or more groups without highly trained personnel. That is the smoothness of the parting plane. Parting planes can be classified as smooth and wavy, or as rough and hackly fractures. Intermediate grades of smoothness make the determination of quality on this basis somewhat arbitrary for about 25% of the boules, but most can be classified easily. To determine the usefulness of this criterion, the following test was made.

From a new quantity of 10 kilograms of boules, two groups totalling approximately 4,000 grams each were selected, the first containing the smoothest boules, and the second, the roughest. Two thousand grams of material from the original quantity was excluded from the test, mainly because of its intermediate smoothness.

Each of the 4,000 gram groups thus selected was divided into two lots, one lot of rough being paired with one of smooth boules for processing comparisons. Two sizes of jewel blanks were then produced from the two pairs of lots, one size from one smooth lot and its corresponding rough lot, and the other size from the other smooth lot and from its paired rough lot.

TABLE 1

SAWING RESULTS

Material Started	(%) Weight of Good Pieces Recovered			No. of Pieces Per Gram of Boules Started	
	Saw boules to slabs	Saw slabs to sticks	Saw sticks to blanks	Squares Sawn	Roundels
Size No. 1					
Smooth parting planes	69%	34%	15%	1.32	1.08
Rough parting planes	63%	38%	11%	0.84	0.62
Size No. 2					
Smooth parting planes	74%	48%	14%	2.10	1.75
Rough parting planes	71%	44%	14%	1.96	1.60

Table 1 shows the recovery, in weight percentages, from each sawing operation, and the number of pieces of each size obtained from a gram of boules started. The net recovery of roundels after sawing, surfacing, and grinding, was 1.08 roundels per gram for smooth boules versus 0.62 roundels per gram for rough boules in size number 1, and 1.75 and 1.60 roundels per gram, respectively, for size 2. The differences are not large, but they are consistent, not only in this experiment but also in an early one based on correlated data; further evidence below indicates that this same difference also continues through the drilling and opening operations.

The above experiment warranted further investigation. The complete orientation data for 24 of the smooth boules and for 25 of the rough ones were recorded in advance by means of back-reflection Laue diffraction patterns. The optic orientation of a considerably larger number of each type had also been determined. The optic orientation is not significantly different in the two types of boules, but the complete orientation with respect to both *c*-axis and *a*-axes shows very significant differences.

Method of orientation study. The methods of orientation study used here are based on *x*-ray diffraction patterns, usually combined with the rapid determination of extinction angle by means of polarized light; this angle is here designated "ρ" and is defined as the angle between the *c*-axis of the crystal and the growth-axis of the boule (or the geometrical axis of a jewel). The optical method is not an essential adjunct to the *x*-ray method, but serves as a useful check. As already noted, this angle may have any value from 0° to 90°. It is most often between 30° and 80° because that appears to be the range favored in the boule-manufacturing process. This angle is determined again by the *x*-ray method, but in addition, the latter method gives a second angular coordinate of orientation, designated "ϕ,"* which is the angle between (1) the plane containing the *c*-axis and an *a*-axis of the crystal, and (2) the plane containing the *c*-axis of the crystal and the growth-axis of the boule (that is, the parting plane). This angle, ϕ, may have any value between 0° and 120°, or by taking into account the symmetry planes of the rhombohedral class to which corundum belongs, ϕ may be limited to values between 30° and 90° if desired. Values larger than 120° would be but symmetrical repetitions of values less than 120° because of the ternary symmetry of the *c*-axis (see Ford, 1932, p. 120, or Winchell, 1943, p. 81). In accordance with the above definitions, (ϕ, ρ) are the 2-circle angular coordinates of the growth axis of the boule, or of the plane of a jewel cut in conventional manner from it. Remembering that the parting plane contains the *c*-axis and the boule-axis, its coordinates are then ($90°+\phi$, 90°).

The *x*-ray method best adapted to the determination of the coordinates defined above is the back-reflection Laue technique, utilizing the general, or "white" radiation from the *x*-ray tube. The resulting pattern is related closely to the gnomonic and stereographic projections, and can often be interpreted by inspection. This pattern can easily be converted to a gnomonic projection in which the center of the projection represents the boule-axis or the jewel-axis to be determined, and it is relatively easy to determine the 2-circle coordinates of this point with respect to the crystallographic axes after location of the latter on the projection. The pseudo-cubic symmetry of corundum makes considerable care necessary in the construction and interpretation of these projections; it also makes the optical method of determining ρ independently very useful.

Presentation of orientation data. When many orientation data are to be studied it is convenient to use the Lambert equal area projection for plotting the 2-circle coordinates of the boule growth-axes, so that a contour diagram can be constructed from the summarized data. The relation of the equal-area, and the stereographic projection is indicated in Fig. 3.

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* The definition here given results in values of ϕ, 60° larger than those given for corresponding faces in the new edition of *Dana's System of Mineralogy*, volume 1, pp. 23–31. The difference is due to the choice of the positive end of an *a*-axis for $\phi=0$, versus the choice of the negative end therefor. Conversion is Winchell to Dana: $\phi'=\phi-60°$ and Dana to Winchell: $\phi'=\phi+60°$. This does not affect the value of ρ.

The azimuthal coordinate, ϕ, is measured by means of the scale of degrees around the primitive circle. The scatter diagrams (Figs. 4–10, A) show not only the points within the range $30 \leqq \phi \leqq 90$, but also all symmetrically equivalent points in the upper half of the rhombohedral crystal (See Ford, 1932, p. 120, or Winchell, 1942, p. 81).

Isopleths ("contour lines") are then drawn showing the density of point distribution on the scatter diagram, and therefore expressing the relative frequency of all possible boule (or jewel) orientations. This can be done because of the special property of equivalence of areas, possessed by the equal area projection. The lines are drawn in accordance with methods outlined in various books on structural petrology or petrofabrics (Sander, 1930, p. 118–135; Fairbairn, 1935, pp. 22–24). If the distribution is perfectly uniform, the concentration will be 1% all over the diagram, provided only that a sufficient number of points has been determined.

Orientations of boules with smooth and rough parting planes. Figure 4 shows the orientation tendencies of boules having unusually smooth parting planes, representative of the boules cited in the experiment described above. Figure 5 represents the complementary boules with rough parting planes. It will be remembered that the smooth boules represented by Fig. 4 yielded consistently better results than the rough boules represented by Fig. 5, as shown in Table 1. It will be noted also that the extinction angles, ρ, indicate very little or no difference between the boules represented in Fig. 4, and those of Fig. 5. It is unfortunate that these same, identical lots cannot be traced through the remaining processing operations, to determine if smooth boules continue to be superior to rough ones. However, an analysis by the same methods, of orientations

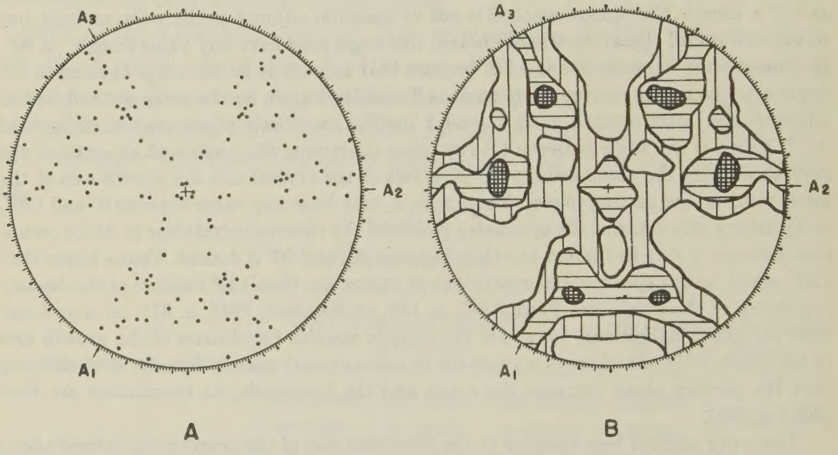

FIG. 4. Orientation of growth directions of 24 boules with smooth parting planes. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. Constructed with 2% movable area.

of jewel blanks that have passed through the most significant later steps of manufacture is possible and will be presented below, showing a very significant correlation with the smooth boules represented in Fig. 4.

General orientation tendencies of all boules. First, however, an analysis of general boule orientation regardless of the quality of the parting plane, extinction angle, or any other criterion, should be presented as background against which to compare observed orientation tendencies to be found in special groups. Figures 6, 7, and 8 show the results of x-ray orientation anaylsis of approximately 150 boules selected at random from three shipments, respectively of white boules from supplier "*X*," red boules from the same supplier, and red boules from supplier "*Y*." Shipments of boules from other suppliers have been too erratic to permit inclusion in this discussion, although individual boules still available in our specimen collections fall nicely into the pattern established by Figs. 6, 7, and 8. It will be noted that there are slight differences between the dominant orientations of "*X's*" white and red boules, but that "*Y's*" red boules show orientations somewhat similar to "*X's*" white ones. These differences probably result from differing orientation-control practices of the two suppliers, and not from any fundamental differences due to the crystallization of corundum boules.

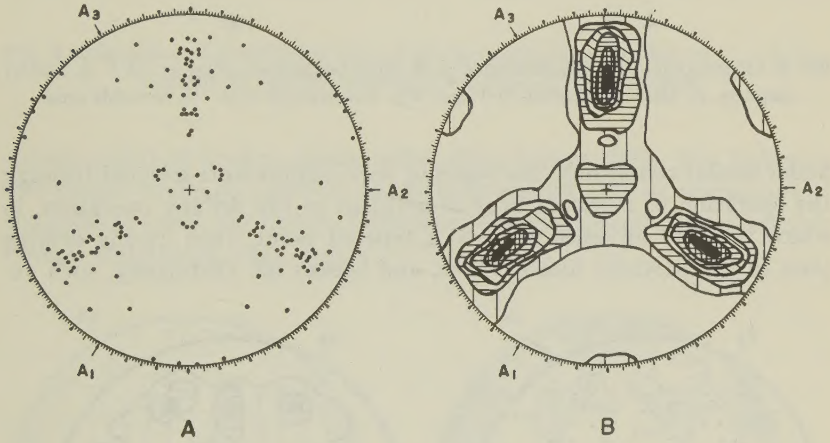

FIG. 5. Orientation of growth directions of 25 boules with rough parting planes. *A*, Scatte diagram. *B*, Density diagram. 0–1–2–3–4–5–6%. Constructed with 2% movable area.

Orientations of successful vs. unsuccessful jewel blanks. This study was originally inspired by the writer's discovery of a box of jewel blanks which had proved themselves definitely superior to other blanks which broke

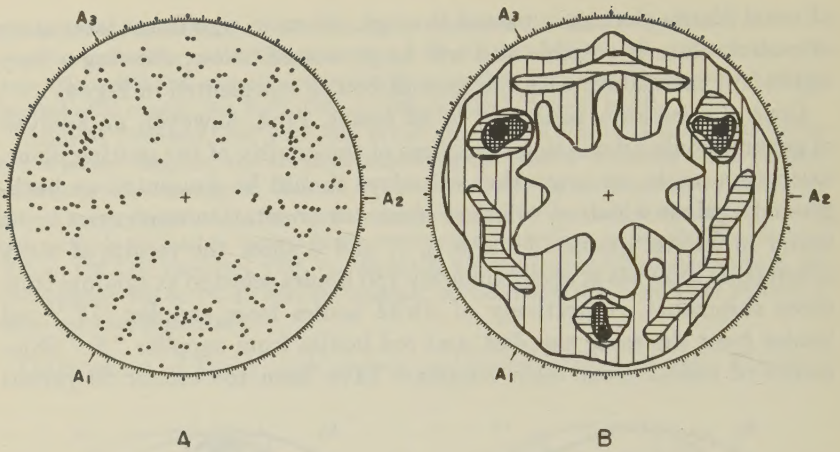

FIG. 6. Orientation of growth directions of 48 white boules from supplier "*X*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3–4%. Constructed with 1% movable area.

under similar conditions. The superior jewel blanks were selected through the operation of a certain type of accident in the drilling operation, in which the drill becomes worn to a tapered point, then during drilling jams in the partially finished hole, and breaks off. Ordinarily, such ac-

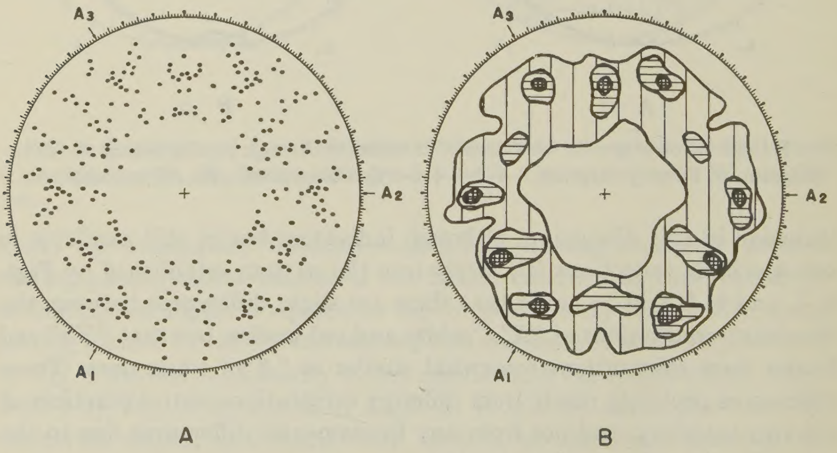

FIG. 7. Orientation of growth directions of 50 ruby boules from supplier "*X*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.

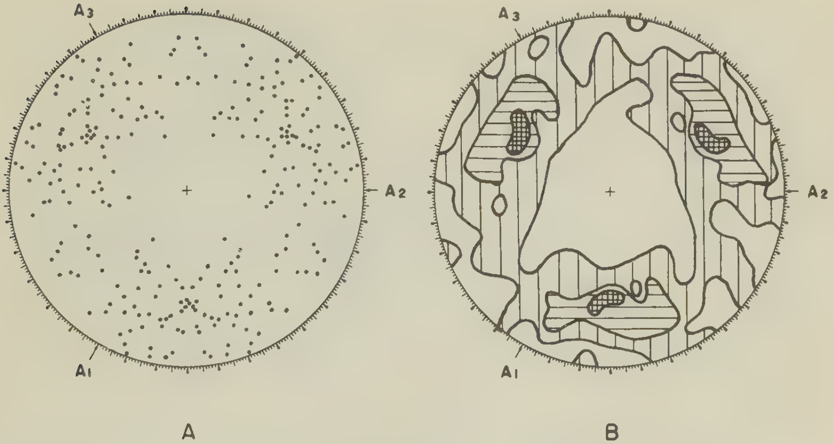

FIG. 8. Orientation of growth directions of 46 ruby boules from supplier "*Y*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.

cidents result in broken jewels rather than broken drills. The following two figures make no pretense at showing orientations representative of the average jewel, but rather of orientation tendencies among remarkably strong, and among weak jewels.

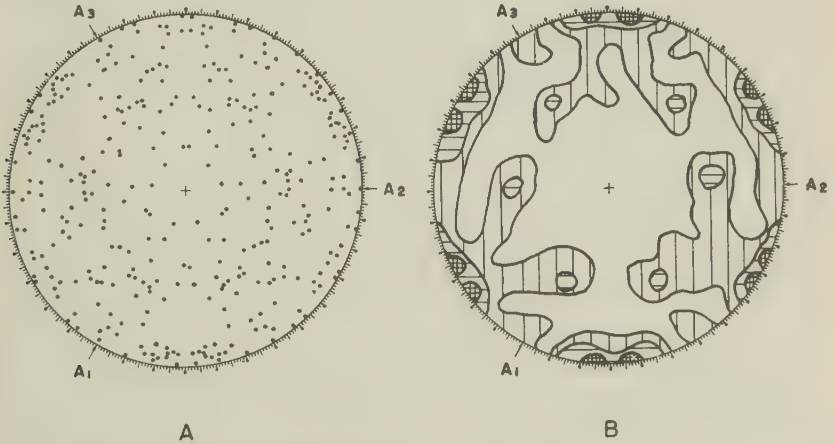

FIG. 9. Orientation of planes (or hole-axes) of 56 jewel blanks in which drills stuck without damage to the blanks. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. Constructed with 1% movable area.

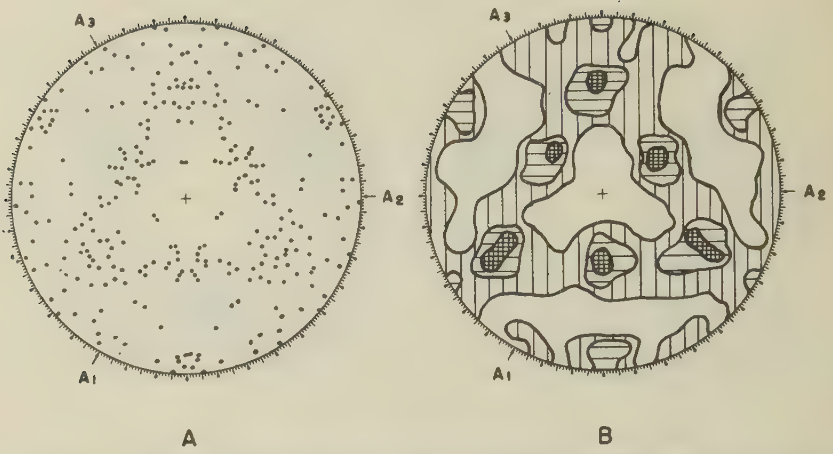

FIG. 10. Orientation of planes (or hole-axes) of 49 jewel blanks that broke during drilling or opening of the holes. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.

Figure 9 shows the scatter and density diagrams of orientation of 56 jewel blanks in which drills were broken as just described. Figure 10 shows the corresponding diagrams for 49 broken jewel blanks. The force required to remove the broken drills mechanically is almost always enough to break the jewel blanks; in practice the drills are therefore removed chemically. All the jewel blanks represented by Figs. 9 and 10 had already withstood the tests of sawing, surfacing, and centerless grinding to make roundels. A comparison of the two diagrams therefore evaluates the strength of jewel blanks against expansive stresses set up in drilling and opening. On the other hand, comparison of Fig. 9 with Figs. 6, 7, and 8 indicates which of the boules were inferior in any of the operations from sawing through drilling. Moreover, it will be seen immediately that the boules with *rough* parting planes (Fig. 5) are strongly correlated with those jewel blanks which *broke* in drilling, (Fig. 10) even after surviving the preceding operations, and that the unusually *smooth* boules (Fig. 4) can be correlated excellently with the *strong* jewel blanks which survived the special accident of stuck drills (Fig. 9). For practical purposes, these conclusions show definitely that a material increase in rate of jewel production could be expected if the boule material should be especially selected for smooth parting planes in preference to rough, hackly surfaces.

CRYSTALLOGRAPHY OF SYNTHETIC CORUNDUM

A limited amount of fundamental information may be derived from the preceding data, in addition to the practical correlations to be found between jewel production rates and boule orientation. Moreover, the enunciation of such additional fundamental information may later lead to further conclusions of value to the manufacturer of jewels as well as to the manufacturer of boules.

Referring to Figs. 6, 7, and 8, it appears that certain crystal forms of corundum may have superior crystallizing power, a conclusion which the makers of the boules could probably confirm or refute in terms of amounts of gas required to grow a given weight of boules. It is understood that orientation control at the boule manufacturing plants is, or soon will be, an accomplished fact. Whether this intention may have resulted from fuel savings due to superior growth tendencies of corundum in certain orientations, or from the demands of the jewel manufacturing industry is known only to the boule makers. A study of energy-entropy relations and their correlation with crystallographic growth directions might lead to significant results, but such a study is outside the scope of this discussion. Conditions of crystallization obviously affect the crystal habit, and therefore the rate of growth of various crystal forms in nature; similarly, conditions of orientation and crystallization must affect the rate of crystal growth in artificially produced crystals.

An attempt to specify the various specially-marked growth axes in terms of Miller-Bravais indices or of Miller indices referred to rhombohedral axes might be valuable as an indication of which orientation should be preferred by jewel makers, and which orientation shunned. Table 2 gives in Miller-Bravais indices the nearest important crystallographic plane to each of the peaks shown in the density diagrams.

TABLE 2

Figure Number	Peak Concentration		
	ϕ	ρ	$h\,k\,\bar{i}\,l$
4	65	52	$33\bar{6}5$
5	30	55	$01\bar{1}1$
6	90	62	$40\bar{4}3$
6	−5 to 65	60 ±	
7	30	58	$01\bar{1}1$
7	60	65	$33\bar{6}4$
7	90	50	$40\bar{4}5$
8	90	52	$40\bar{4}5$
9	60	50	$11\bar{2}2$
9	85	90	$81\bar{9}0$
10	30	55	$01\bar{1}1$
10	90	30	$10\bar{1}2$

Information on cleavage and parting planes may be obtained from a study of Figs. 9 and 10. Figure 9 shows high concentrations of successfully drilled jewels at the point (85°, 90°), corresponding roughly to a plane with indices $\{10\bar{1}0\}$, or more exactly to $\{15.2.\overline{17}.0\}$. About 3 to 4 times as many drilled blanks showed this orientation as would have been the case had the orientation dots been distributed uniformly in all parts of the diagram. Ford (1932, p. 481) mentions a commonly developed parting parallel to the basal pinacoid $\{0001\}$. If such a weakness existed in these jewels, it could hardly have failed to show up through the breaking of the jewels in this orientation, and their consequent elimination from the class, "unusually strong in drilling." Figure 10 suggests by the distribution peaks that a likely plane of breakage is the second order prism $\{11\bar{2}0\}$. Breakage approximately parallel to this form could account for peaks of breakage of jewels whose axes lie 90° from it. The distribution of ridges in Fig. 10 suggests an alternative hypothesis, however, in the possibility that breakage occurred parallel to the planes of $\{01\bar{1}1\}$. If this were the one and only plane of weakness, practically all the broken jewels indicated in Fig. 10 would have had their holes drilled parallel to one or more of the faces of this form. Additional commentary on the possibility of a cleavage parallel to the second order prism is afforded by Fig. 5, in which almost all of the boules with rough, irregular parting planes are shown to have growth axes in the rhombohedral zone, and parting planes therefore parallel to the second order prism. It would be surprising if the poorest parting planes should be parallel to a good cleavage; quite the converse would be expected. Figure 4, on the other hand, in which growth axes of boules with smooth parting planes lie mostly in the second order pyramid zone, seems to indicate a tendency to break parallel to the first order prism $\{10\bar{1}0\}$.

Parting surfaces parallel to the unit rhombohedron $\{10\bar{1}1\}$ are sometimes developed very highly. When fracture occurs on such planes, the resulting surfaces may be perfectly flat over large areas, and always give excellent signals in the optical goniometer. This parting is frequently responsible for small chips out of corners and edges of jewel blanks, and indeed it sometimes gives much trouble in the processing of blanks for pallet stone jewels, which are shaped simply like tiny monoclinic crystals bounded by surfaces belonging to the three pinacoids. Such jewels are often as small as 0.5 mm. in thickness, and must have highly polished surfaces and perfect, unfrayed edges. The artificial production of such parallelepipedons to small dimensions from a brittle material like corundum offers a very nice problem in tool design, for the dimensional tolerances on these jewels are very limited. Vibration of saw blades in sawing boules or at other sawing steps, and vibration or too coarse diamond powder in laps used for surfacing small corundum pieces often seem to be responsible for development of the rhombohedral parting.

The exterior, convex surface of most boules is composed of myriads of tiny facets parallel with the faces of the basal pinacoid, the unit rhombohedron, and the first and second order prisms. As a result of this condition almost the entire convex surface of the boule glitters brightly under certain conditions of illumination. Under these conditions, slight imperfections of crystal structure along definite lines and bands are visible. This probably is the lineage structure described by Buerger (1934). The brightest reflection thus obtained is usually due to $c\{0001\}$. None of these reflections ever gives a very good signal in the optical goniometer.

CONCLUSIONS

The ratio of good jewels to corundum input can be correlated with crystallographic orientation of the raw material boules. An outstandingly poor orientation is more frequently found among boules with rough, hackly parting planes than among those with smooth ones. Such boules most often grow in a direction approximately normal to the planes, $\{01\bar{1}1\}$ and $\{10\bar{1}2\}$. Favorable orientations for boule axes are not so definitely located, but appear to be near $\{11\bar{2}2\}$ and $\{81\bar{9}0\}$ or $\{81\bar{9}2\}$. A uniform control of boule axes in one or the other of these orientations would probably result in a marked decrease in the rate of jewel breakage during fabrication.

One empirical method for partial control of boule orientation depends upon the fact that those with $\{01\bar{1}1\}$ orientation generally split with a rougher fracture than those with other orientations. This fact may indicate that the parting on $\{11\bar{2}0\}$ cited in reference books (Ford, 1932, p. 481), on the natural mineral is not so well developed in synthetic material as another parting, not mentioned in the textbooks, parallel to $\{10\bar{1}0\}$.

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GRAIN SIZES AND SHAPES OF VARIOUS MINERALS IN IGNEOUS ROCKS

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ABSTRACT

Conflicting statements are found in geological literature regarding grain sizes of various minerals in igneous rocks. The writer has found no general information on the subject. A series of 200 rocks involving 40,000 to 50,000 measurements were studied in thin sections at the University of Minnesota. Results of this study are used to arrive at some general conclusions.

Average grain size for a mineral differs in different granitoid rocks. Any one mineral in a series of several hundred granitoid igneous rocks shows an average grain size which differs widely from the average grain size of another mineral in the same series of rocks. Different minerals vary in average shape as well as average area. There is some suggestion that difference in grain size is due largely to abundance or scarcity of corresponding material in the parent magma.

Workers in petrography seem to have no generalized data concerning relative grain sizes of various minerals in igneous rocks. Rubey[1] says he "is aware of no common or at any rate no generally recognized, relationships of crystal sizes that result in marked differences in the grain size of the various mineral species present in igneous or metamorphic rocks." On the other hand, Martens[2] writes that he "can not agree with Rubey in his statement that the assumption of a homogeneous size-distribution of the heavy mineral grains at the source seems justifiable, but, rather, believes that differences in size-distribution of different minerals at the source may be as important as any of the other factors causing sands of different coarseness, derived from the same source, to have different relative amounts of heavy minerals."

Neither statement is supported by quantitative data. The writer has found no general study of relationships of grain sizes of minerals. In the present study two hundred granitoid igneous rocks were examined in the hope that these would furnish a basis for at least preliminary generalizations with respect to relative grain sizes of a few common minerals. A few slightly metamorphosed equivalents of igneous rocks, where there is no evidence of crushing or recrystallization, were included in the study.

Thanks are due Professor F. F. Grout for editing the paper, and to Miss W. H. Eckstein, in the Department of Geology, University of Minnesota, for helping to compute some of the results.

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[1] Rubey, W. W., Size-distribution of heavy minerals within a water-laid sandstone: *Jour. Sed. Petr.*, **3, 4,** 23 (1933–34).

[2] Martens, J. H. C., Beach sands between Charleston, South Carolina, and Miami, Florida: *Bull. Geol. Soc. Am.*, **46,** 1586 (1935).

"Grain size," as used throughout this paper is measured in thin sections in two dimensions and computed as an area. Where the outline of grains was irregular or rounded, for the purpose of consistency, maximum length and width were recorded in each case. Strictly, grain size involves three dimensions or volumes, but since most mineral grains would be difficult or impossible to isolate from fresh igneous rocks, and since areal ratios approximately correspond to volume ratios,[3] it was decided that best results could be obtained for a variety of minerals by measuring grain sizes in thin section under a microscope.

It is noteworthy that grain sizes in thin section are not always maximum cross-sections of the grains. Many of them will be so oriented and cut as to give areas smaller than the maximum, but results will be about as much affected for one mineral as for others, and will give a basis for comparison of a series of minerals even if not the actual sizes. Calculated results represent grain size in a specimen but not necessarily in a large rock body where locality is given, since a single thin section may not be representative of that rock body.

Only minerals believed to be primary were measured for comparison. For a pseudomorph the original mineral was recorded if there was evidence of its nature. An average of over 100 grains per slide was measured, or a total of from 40,000 to 50,000 measurements in all.

All granitoid and coarse diabasic rocks in the petrography laboratory at the University of Minnesota were made available to the writer. They were collected from many states of the United States and at least a dozen other countries, some being from type localities.

The study involved compilation of a mass of data and then arrangement and calculation of results. The primary minerals in a slide were listed on a sheet (Table 1 is an example). The rock number, classification, and location were recorded at the top. Measurements were made by a micrometer ocular consecutively without arbitrary selection for each mineral. Where less than six grains of a mineral were found, the measurements were not considered representative and, therefore, not used in computing average grain sizes for that mineral. Traverses at close intervals were made parallel to the length of the slide. Many rocks were represented by one slide, but where several slides were available most or all of these were used to obtain measurements.

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[3] Holmes, A., *Petrographic Methods and Calculations:* Thos. Murby and Co., London 310–312 **(1930).**

TABLE 1. EXAMPLE OF AN ORIGINAL SHEET SHOWING HOW MEASUREMENTS WERE TABULATED

Rock Number: GP. 397-6 (Biotite Granite)
Ascutney Mountain, Vermont

Readings in $\frac{\text{mm}}{20}$			Readings in $\frac{\text{mm}}{65}$					
Quartz	Orthoclase	Plagioclase N<CB	Biotite	Magnetite	Sphene	Apatite	Allanite	Zircon
20×15	65×58	25×20	10×4	9×9	9×5	5×2	13×13	2×2
10×9	15×9	9×7	31×29	9×5	10×6	3×2	11×10	2×1
13×12	16×16	4×2	14×8	9×9	19×8	5×4	7×3	2×1
9×7	30×19	8×3	18×18	8×4	7×5	2×2	11×4	1×0.5
13×9	11×6	10×7	17×8	1×1	5×2	5×4	25×12	3×2
10×5	7×3	35×13	15×15	2×1	9×6	5×1	6×4	3×1
20×15	94×52	27×17	20×12	5×4	15×10	4×4	35×11	2×1
16×15	35×30	11×7	14×8	15×9	14×4	12×5	30×7	4×3
13×10	26×21	12×8	9×9	4×4	29×9	6×4	6×3	
14×8	67×25	11×7	4×3	9×7	14×4	4×1		
6×4	28×20	49×16	17×8	7×7	8×4	6×2		
8×7	24×13	18×10	16×10	6×6	11×5	12×6		
6×5	72×55	5×3	16×7	1×1	28×9	9×5		
6×4	42×22	30×9	25×11	8×6	55×14	1×1		
4×3	29×19	20×15	25×15	8×5				
8×8	44×40		64×50	8×8				
1×1	103×50							
22×17								

Some difficulty was encountered in determining boundaries of opaque or isotropic grains where these occurred in clusters. Wherever possible such clusters were avoided, but where measurements could not be obtained otherwise an attempt was made to determine boundaries by differences in lustre under reflected light when the stage was rotated.

From the data sheets a maximum and minimum area* for each mineral were found and the average grain size was calculated; all being listed as in Table 2.

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* For this maximum and minimum, *lengths* were chosen. In 19 out of 20 cases which were checked, maximum lengths corresponded to maximum *areas*. On the basis of this finding, lengths were considered reasonable indications of size.

TABLE 2. MAXIMUM, MINIMUM, AND AVERAGE GRAIN SIZES OBTAINED FROM DATA IN TABLE 1

Rock Number: GP. 397-6 (Biotite Granite)
Ascutney Mountain, Vermont

	Readings in $\frac{mm}{20}$			Readings in $\frac{mm}{65}$					
	Quartz (18)*	Orthoclase (17)	Plagioclase N<CB. (16)	Biotite (16)	Magnetite (16)	Sphene (14)	Apatite (15)	Allanite (9)	Zircon (8)
Maximum grain size	22×17	103×50	49×16	64×50	15×9	55×14	12×6	35×11	4×3
Minimum grain size	1× 1	7× 3	4× 2	4× 3	1×1	5× 2	1×1	6× 3	1×0.5
Average grain size	11× 8.5	42×27	19×11	20×13	6.8×5.4	17× 6.5	5.4×3	16×7.4	2.4×1.4

* Represents number of grains measured.

The rocks were divided into three groups:

I. Silicic, to include granites and syenites except nepheline (or other feldspathoid) syenites.
II. Medium, to include feldspathoid syenites, monzonites, and diorites.
III. Basic, to include gabbros, and ultra-basic rocks.

On this basis 92 of the rocks were found to be in group I, 55 in group II, and 53 in group III.

Minerals as determined in slides were listed under each group, and the average grain size of the minerals for the whole group determined. These averages for all the minerals in each group, together with the number of rocks used in obtaining the average, are listed in Table 3.

TABLE 3. AVERAGE GRAIN SIZES OF VARIOUS MINERALS IN ROCKS

(Areas are in sq. mm.; figures in parentheses following areas, indicate number of rocks from which average is derived.)

Mineral	Silicic	Medium	Basic
Plagioclase	1.3 ×0.75 =0.975 (87)	1.1 ×0.60 =0.66 (48)	1.3 ×0.60 =0.78 (43)
Microcline	1.15 ×0.75 =0.87 (49)	2.05 ×1.15 =2.36 (4)	(0)
Orthoclase	1.25 ×0.80 =1.0 (76)	1.4 ×0.75 =1.05 (21)	1.6 ×0.90 =1.44 (5)
Microperthite	1.8 ×1.05 =1.89 (7)	1.95 ×0.75 =1.46 (2)	(0)
Quartz	0.85 ×0.55 =0.468 (88)	0.49 ×0.34 =0.166 (26)	0.39 ×0.26 =0.101 (4)
Hornblende	0.80 ×0.48 =0.384 (38)	0.85 ×0.50 =0.425 (27)	0.95 ×0.55 =0.525 (9)
Pyroxene	0.77 ×0.44 =0.339 (3)	0.824×0.421=0.347 (27)	1.114×0.696=0.697 (35)
Biotite	0.70 ×0.31 =0.217 (62)	0.70 ×0.375=0.262 (36)	0.70 ×0.38 =0.266 (16)
Olivine	(0)	0.50 ×0.37 =0.185 (2)	0.9 ×0.6 =0.54 (26)
Nepheline	(0)	1.1 ×0.85 =0.935 (10)	0.80 ×0.45 =0.36 (2)
Allanite	0.20 ×0.108=0.0216 (6)	0.43 ×0.29 =0.125 (3)	0.335×0.195=0.065 (1)
Sphene	0.23 ×0.114=0.0262 (20)	0.31 ×0.154=0.048 (20)	0.20 ×0.132=0.0264 (2)
Fluorite	0.35 ×0.22 =0.077 (5)	0.17 ×0.085=0.0145 (1)	(0)
Apatite	0.12 ×0.05 =0.006 (58)	0.17 ×0.07 =0.012 (51)	0.23 ×0.10 =0.023 (27)
Zircon	0.063×0.042=0.0026 (43)	0.066×0.046=0.003 (7)	0.057×0.035=0.002 (4)
Magnetite	0.185×0.123=0.023 (66)	0.185×0.14 =0.026 (42)	0.37 ×0.28 =0.103 (47)
Muscovite	0.445×0.23 =0.103 (11)	0.26 ×0.103=0.027 (2)	(0)
Pyrite	0.137×0.088=0.012 (3)	0.23 ×0.17 =0.039 (6)	0.20 ×0.132=0.026 (8)

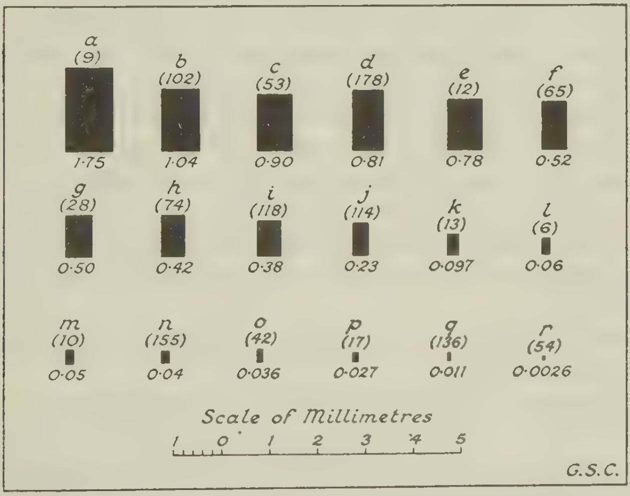

FIG. 1. Average shapes and areas of minerals in 200 thin sections of medium granitoid igneous rocks. Numbers above blocks indicate number of rocks in which the mineral was studied. Numbers below blocks indicate areas in square millimeters.

a—Microperthite
b—Orthoclase
c—Microcline
d—Plagioclase
e—Nepheline
f—Pyroxene
g—Olivine
h—Hornblende
i—Quartz
j—Biotite
k—Muscovite
l—Fluorite
m—Allanite
n—Magnetite
o—Sphene
p—Pyrite
q—Apatite
r—Zircon

Members of isomorphous series and similar groups were combined and listed under group names.

Average grain sizes, shapes, and areas are shown in Fig. 1 where minerals are arranged in descending order of size. Available data for garnet, tourmaline, pyrrhotite, hematitie, carbonate, epidote and chlorite are so meager that they have been omitted from Table 3 and Fig. 1. The results would not modify the general conclusions.

It is clear from Table 3 that grain sizes of some minerals differ considerably with composition of the rock in which they occur. Average quartz grains in silicic rocks are more than 4 times as large as those in basic rocks, and average magnetite and apatite grains in basic rocks are approximately 4 times as large as those in silicic rocks. Average pyroxene grains in basic rocks are twice as large as those in silicic rocks. This may mean that grain size is related to abundance of a mineral in igneous rocks. Essential and varietal minerals all have a larger average grain size than accessory minerals. However, there are many exceptions to this trend. Orthoclase and hornblende, for instance, have larger average grain sizes in basic rocks than in silicic rocks. Many more rocks would have to be carefully studied before generalizations could be made.

In Fig. 1 it is evident that differences in grain sizes of different minerals are pronounced. The average orthoclase area is 400 times as large as the average zircon area. Minerals in rocks have differences in shape as well as size. Average pyrite and magnetite grains are nearly equidimensional, while average apatite, zircon, and sphene grains are elongated. Average acmite-augite grains are more elongated than augite grains.*

There is a wider range between maximum and average grain size for large grained minerals than for small grained ones; but the ratio of maximum grain size/average grain size is generally smaller in the large grained minerals.

From the two hundred rocks which were studied, several general conclusions are drawn:

1. Average grain size for a mineral differs in different granitoid igneous rocks.
2. Any one mineral in a series of several hundred granitoid igneous rocks shows an average grain size which differs widely from the average grain size of other minerals in the same series of rocks.
3. Different minerals in thin sections of granitoid igneous rocks differ in average shape as well as average area.

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* Each member of the pyroxene group was determined and measured separately but all have been listed under the group name in final tabulations.

4. The characteristic essential and varietal minerals are strikingly larger than the usual accessory minerals. There is a suggestion that this difference may be due largely to the abundance or scarcity of the corresponding material in the parent magma, but data are rather meager for this last suggestion.

THE KAOLINITE STRUCTURE OF AMESITE, $(OH)_8(Mg,Fe)_4Al_2(Si_2Al_2)O_{10}$, AND ADDITIONAL DATA ON CHLORITES

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ABSTRACT

An investigation of amesite with *x*-rays discloses that the mineral cannot be a simple chlorite. It has essentially a kaolinite structure, with which a few chlorite units are interstratified. As chlorites increase in Al at the expense of Si, there is a shrinkage normal to the basal cleavage. Reasons for this decrease as well as for the instability of the chlorite structure when the ratio of trivalent ions to Si reaches a certain value are suggested.

INTRODUCTION

Amesite has been reported from only one locality, namely, Chester, Mass. On account of its unusual chemical composition and properties, it has attracted wide-spread attention. It has commonly been regarded as a chlorite. Tschermak, in 1890, called it the chlorite end member of an isomorphous mixture of chlorites and serpentines. McMurchy (3) determined the structure of the chlorites in the writer's laboratory in 1934 and *x*-rayed, among others, amesite. It was noticed then that there was sufficient difference between its structure and that of the chlorites proper so that it could not be included with the latter. In connection with the study of other layer structures, the writer has investigated amesite recently and has come to the conclusion that it has a kaolinite structure. He is indebted to the Graduate School of the University of Minnesota for aid in this study, and to Dr. W. F. Foshag for the specimen of amesite from the type locality.

PROPERTIES AND CHEMICAL COMPOSITION

Amesite occurs in close association with diaspore, magnetite, and corundophilite. Since the specimen used is the identical one described and analyzed by Shannon (2) in 1921 (U. S. National Museum #80715) his description is given below:

> The specimen consisted of a large flat mass of diaspore showing pale grayish-pink cleavages several inches broad where broken and containing small cavities filled with interlacing needle-like crystals of diaspore. One side of the specimen is completely coated with a layer of flat amesite crystals of a pale green color somewhat iron stained. Scattered through the mass of the diaspore there are variously oriented crystals of amesite, large octahedrons of magnetite, and crystals of dark red to black rutile. The amesite occurs in tabular hexagonal crystals with dull prismatic faces. They reach an extreme diameter of 1 cm. with a thickness of 3 to 5 mm. By breaking up the diaspore, clean crystals were

readily secured and these, when ground, were used for analysis. The material was perfectly homogeneous and free from impurities as shown by optical study.

The amesite has a uniform pale bluish-green color. The luster is pearly to somewhat metallic on cleavage surfaces. In thick pieces the mineral is translucent to almost opaque. Thin fragments are transparent. The powder is white with a very faint tinge of green. The mineral has a micaceous basal cleavage which, however, is not nearly so perfect as in most crystallized chlorites. Laminae are rather brittle and break in a manner suggesting a very imperfect prismatic cleavage. The hardness is about 2.3, as it scratches gypsum readily, but is scratched with great ease by calcite. The specific gravity as determined on approximately 3 grams of coarse fragments in a pycnometer is 2.77.

Under the microscope cleavage plates of the amesite are dark in all positions between crossed nicols. Examined in convergent light a black cross is obtained, which separates slightly on rotation of the stage indicating that the mineral is biaxial with the axial angle, $2V$, very small, acute bisectrix normal to the perfect cleavage. The optical character is positive. The mineral is colorless as seen under the microscope. The refractive indices measured by the immersion method were found by Dr. E. S. Larsen to be as follows:

$$\alpha=1.597\pm.003,\quad \beta=1.597\pm.003,\quad \gamma=1.612\pm.003,\quad \gamma-\alpha=.015\pm.003.$$

Heated before the blowpipe the amesite swells somewhat and exfoliates slightly, becoming silvery brownish-white in color. It is infusible. It does not become magnetic when roasted on charcoal. It yields considerable water in the closed tube. The main portion of the water is basic, coming off only at a dull red heat. The mineral is partially decomposed by boiling in sulphuric, nitric, or hydrochloric acid with separation of flocculent silica.

The observations of the writer agree closely with those of Shannon. His chemical analysis is included in Table 1.

Table 1. Chemical Composition and Ionic Distribution of Amesite

	1	2	3	4	5	6	7
		Mol. ratio	Oxide ratio adjusted	+ ions	+ charges	Occupied + positions	Theoretical anions positions
SiO_2	20.95	.3488	16.00	16.0	64.0	32 tetrahedral	80 O
Al_2O_3	35.21	.3454	15.84	31.7	95.1		
FeO	8.28	.1152	5.28	5.3	10.6	47.5 octahedral	
CaO	0.58	.0103	0.47	0.5	1.0		
MgO	22.88	.5674	26.03	26.0	52.0		
MnO	tr.						
H_2O+	13.02	.7225	33.14	66.3			64 OH
H_2O-	0.23						
Total	101.15				222.7		224 — charges
Mol. W.			4628				

Since amesite is unquestionably a layer silicate of pseudo-hexagonal or hexagonal unit cell and has an x-ray period of 14.03 Å, or a multiple of this value, normal to the layers, its structure must be either that of chlorite, kaolinite, antigorite, or a combination of two of the three. Its chemical composition corresponds to any one of the three, of course, since they have the same number of ionic positions in their lattices. If we make the unit cell twice as large as the accepted one for chlorite, we have 80 O, 64 (OH), 32 (Si,Al) tetrahedral and a maximum of 48 (Mg,Al,Fe) octahedral positions. In columns 3 and 4 of Table 1, it is assumed that Si occupies 16 positions. The other 16 tetrahedral ones are filled by Al. This leaves a total of 47.5 cations to occupy the 48 octahedral positions. The positive charges of column 5 balance the negative charges of column 7, especially if a slight adjustment be made in the number of (OH) and O ions. The formula is: $(OH)_{64}(Mg, Fe'')_{31.8}Al_{15.7}(Si_{16}Al_{16})O_{80}$. The molecular weight of this unit cell is 4628. Its volume is $2(5.30\times 9.20\times 28.06) = 2738$ A^3. The theoretical density then is 2.789, in excellent agreement with the observed value (Table 3). All determinations, unless otherwise stated, were made in Thoulet solution. McMurchy's specific gravities were determined with the pycnometer and agree well with the new densities of Table 3.

X-RAY DATA

It was not intended to go into an exhaustive study of the space group and atomic coordinates of amesite in this investigation. It is probably

TABLE 2. THEORETICAL AND OBSERVED RELATIVE INTENSITIES OF BASAL REFLECTIONS OF AMESITE AND CHLORITE STRUCTURES. FE AND CU RADIATION. 57.3 MM. CAMERA RADIUS

Order of reflection	002	004	006	008	0010	0012	0014	0016	0018	0020	0022	0024	0026	0028	0030	0032
Theor. I. Kaolinite structure with amesite composition	0	74	0	82	0	22	0	3	0	13	0	17	0	14	0	15
Obs. I. Amesite	0	64	8	80+	6	24	very faint	8	0	16	0	24	0	24	0*	24*
Theor. I. Chlorite structure with amesite composition	7	43	51	53	18	3	10	0	1	13	0	15	0	16	0	9
Obs. I. Chlorite-corundophilite	13	54	48	80	40	0	20	0	0	20	0	20	0	26	**	**
Theor. I. Kaolinite layers with amesite composition, facing one another	2	58	12	59	18	7	1	1	7	0	12	15	0	9	7	0

* Observed with Cu radiation.

** Outside of range of Fe radiation.

not practical to do so as the mineral seems to have random shifts along the *b* axis as was shown for talc and related structures by Hendricks (4, p. 536). In order to determine whether amesite is a chlorite or kaolinite it is sufficient to thoroughly investigate the basal reflections of the minerals.

This was done by rotating small thin cleavage pieces of the minerals in the *x*-ray beam. Filtered Cu and unfiltered Fe radiations were used with cameras of 57.3 mm. radius. The arrangement was such that reflections of 14 Å spacing would easily register on the film. The observed intensities are recorded in Table 2. Since the unit of spacing normal to the cleavage is about 28 Å in chlorites, the first visible reflection near 14 Å would be 002. This is the spacing also assumed for amesite, though it may be too large by a factor of 2. For comparison, the observed basal intensities for corundophilite have been listed in Table 2. This is the chlorite which occurs with amesite at the type locality at Chester, Mass. A good specimen of it was available for this investigation. Its chemical analysis and other properties were described by Shannon (2). It is possible that his and the writer's corundophilite differ slightly in composition, as suggested by the small difference in theoretical and observed densities (Table 3). No *x*-ray data on powders are included here, though they were carefully studied. They have been previously recorded by McMurchy (3) and later by Hallimond and Bannister (6).

Pauling (1), McMurchy (3), and the writer (5) have shown the stacking of single layers of kaolinite, talc, pyrophyllite, and brucite which lead to structures with kaolinite-chlorite formulas. If one excludes the serpentine structures described by Warren and Bragg, there are only three possibilities:

1. The chlorites proper (1) and (3).
2. The kaolinites proper (1) and (5).
3. A structure of kaolinite layers in which adjacent layers would not be pointing in the same direction but would be turned 180° with respect to each other, in other words, would be facing each other.

The theoretical intensities of the basal reflections of each of these have been computed for the chemical formula of amesite and are recorded in Table 2. It may be mentioned here that the observed intensities of chemically quite different chlorites seem to be about the same. In other words, leuchtenbergite, sheridanite, corundophilite, and others fairly high in iron show about the same intensities though the theoretical ones differ considerably.

Examination of Table 2 shows that amesite cannot have the structure of 3, for no reflections are observed for 0018, 0022, and 0030. Also, 0032, which should be absent, is quite strong. Structure 1, that of the chlorites proper, is not possible because 002 is not observable on any of the films.

0012, which should be practically absent is quite strong, and 006, 0010, and 0014, which should be strong, are weak, and 0014 is extremely weak.

There remains only the kaolinite structure for which agreement would be very good if it were not for the presence of weak reflections at 006 and 0010. The latter is not visible in powder photographs. At first it was thought that possibly a little chlorite was in parallel intergrowth with amesite proper. This is not possible for three reasons: (a) Regardless of the place on the specimen from which the four samples for examination were taken, the intensities in all were alike; (b) The unit cells of amesite and corundophilite (or any other chlorite) are sufficiently different in size so that a mechanical mixture of the two would have been readily detected; (c) The optical properties of different specimens of amesite are quite constant.

PROBABLE STRUCTURE

Pauling (1, p. 578) in 1930 was of the opinion that a kaolinite structure with a large amount of Mg in place of Al is not possible because a Mg octahedral layer would be too large for the Si_4O_{10} tetrahedral layer. Distortion and warping would result. In amesite this tetrahedral layer has the formula $Si_2Al_2O_{10}$, and, therefore, is considerably larger. This case is quite analogous to that of cronstedtite described by Hendricks (4) where the tetrahedral layer is $Si_2Fe'''_2O_{10}$. The corresponding dimensions of the three minerals are as follows:

	a_0	b_0	Normal to (001)
kaolinite	5.14	8.90	7.14
amesite	5.30	9.20	7.015
cronstedtite	5.48	9.49	7.08

The contraction of amesite in the direction normal to the base is conspicuous but probably not much greater in proportion than in cronstedtite with its larger Fe''' ions. The contraction is distributed over the whole length of *c*, though probably the largest proportion occurs between the layers for which the distance between centers of O ions and (OH) ions was assumed, as 2.68 Å instead of 2.78 Å in kaolinite. The forces which hold adjacent layers in the actual mineral together are certainly greater than in talc or kaolinite, as may be demonstrated by splitting the mineral.

The weak reflections for 006 and 0010 and the very faint one for 0014 which do not belong to the kaolinite structure call for some explanation. If a unit of chlorite structure were inserted between packets of 10 to 16 layers of kaolinite structure, all the reflections could be accounted for. The individual chlorite layers could be of the same dimensions as the amesite units under these conditions. They may be considered essential to the structure to counteract any stresses otherwise present in a struc-

Table 3. Lattice Constants and Distribution of Positive Ions in Chlorite and Kaolinite Structures

	Spacing 002	a_0	b_0	Number of + ions in 80 positions						Densities	
				Octahedral and brucite layers				Tetrahedral layers		Theor.	Observed
				Mg+Ca	Fe″	Fe‴	Al	Si	Al		
Leuchtenbergite, Philipsburg, Mont.*	14.21	5.30	9.19	41.4			6.6	23.2	8.8	2.636	2.606
Sheridanite, Miles City, Mont.*	14.20	5.32	9.21	36.6	0.2	0.8	10.4	20.9	11.1	2.664	2.668
Chlorite, Burra Burra, Tenn.*	14.18	5.32	9.21	31.1	5.6		11.3	20.5	11.5	2.705	2.756
Prochlorite, Trumbull, Conn.*	14.14	5.35	9.27	24.6	18.3		8.1	19.4	12.6	2.812	2.941[3]
Chlorite,[1] Bolivia,*	14.12	5.37	9.30	10.1	25.7		12.2	19.7	12.3[1]		
Corundophilite, Chester, Mass.	14.12	5.35	9.26	27.8	8.9	2.1	9.2	18.4	13.6	2.816	2.852
Kaolinite, Brooklyn, N. Y. (5)	14.28	5.14	8.90				32	32.0		2.589	2.585
Amesite, Chester, Mass.	14.03	5.30	9.20	26.5	5.3		15.7	16.0	16.0	2.789	2.782
Cronstedtite, Cornwall (4)[2]	14.16	5.48	9.49	1.4	35.8	7.7	1.1	16.8	Fe‴ 15.2	[2]	3.445

* Specimens used by McMurchy (3) were reexamined under the same conditions as amesite and corundophilite. The densities were found with Thoulet solution.

[1] The formula of the chlorite from Bolivia is only approximate since no accurate density was available and the analysis is incomplete, adding up to 91.17% and 4.28% insolubles.

[2] The formula for cronstedtite was adjusted by the writer on the basis of a density of 3.445 determined by Gossner (4).

[3] The formula is based on the observed density. See Table 4.

ture of amesite composition complying with the space group requirements of a true kaolinite. If this interpretation is accepted, amesite has a superlattice cell of large dimensions in the direction of the *c* axis.

In an effort to find a reason for the fact that amesite and cronstedtite do not form chlorite structures, Table 3 was prepared. Wolf von Engelhardt (7) has prepared a similar one of chlorites for the purpose of showing the changes in lattice dimensions with changes in composition. He has included the chlorites which are very high in iron, as thuringite and bavalite. Since the analyses of these iron chlorites were not made on exactly the same material as the *x*-ray photographs, the writer felt they should not be included in Table 3. Engelhardt comes to the conclusion that increases in Fe cause most of the shrinkage along *c* and expansion parallel to *a* and *b*. This can be only part of the explanation, for it does not account for the shrinkage in corundophilite and amesite. The writer has arranged the minerals in the order of the lengths of the 002 spacing. It will be noticed that corresponding to a decrease in 002, there is an increase in substitution of Al (Fe''' in cronstedtite) for Si. The chlorite from Bolivia seems to be the only one not in agreement. Since the analysis of this specimen is only a partial one (see footnote under table) the discrepancy may not be real. It is reasonable to expect the attraction between adjacent layers to rise as the + charges in the tetrahedral layers decrease, as they would with an increase of Al in them. That the resulting shrinkage is not proportional to the percentage of Al is due to other substitutions taking place simultaneously.

As Al or Fe''' increases in the tetrahedral layers of the talc units, there must be a corresponding Al increase in the brucite layers between them. In other words, if amesite had a chlorite structure, all of the Al ions not substituting for Si should be concentrated in the brucite layers. Three-fourths of the divalent ions would be in the octahedral layers of the talc units. This segregation of di- and trivalent ions into separate layers should cause unstable structures. The kaolinite structure is not subject to this instability for it possesses only one type of layer in which all these ions are lodged.

SOME DISCREPANCIES IN CHLORITES

It is unusual to have several analyzed chlorites at one's disposal, on which *x*-ray and density determinations can be made. It may be proper, therefore, to call attention to certain discrepancies between calculated and observed densities of the prochlorite from Trumbull, Conn. (see Table 3). This mineral was carefully analyzed by Shannon (8, p. 473), who called particular attention to the relatively large amount of CaO in it. The writer obtained a part of this analyzed material from Dr. W. F. Foshag and made three density determinations on it. One with a fused silica pycnometer on 0.4 grams resulted in 2.95, and two with Thoulet solutions were 2.939 and 2.948. Inspection of Table 4 shows that this density is considerably higher than the theoretical one of 2.812. In column 3, Table 4, the 80 cations required to fill the unit cell are listed. It will be observed in column 4 that they have only 217.2+ charges instead of the usual 224. Also, instead of about 64 (OH) ions, only about 40 are present. An adjustment to reach agreement with the observed densities results in columns 5, 6, and 7. It will be noticed that there are about 83 cations for 80 positions. It takes 92 O and 42 (OH) to neutralize them. In other words, 12 (OH) positions are occupied by O, while 10 OH positions are vacant. If the chemical analysis is correct—and there is no reason to doubt it—three cations, probably the Ca ions, must be in new and unusual positions between the talc units and the brucite ones. They would correspond to the K or Ca ions in micas or brittle micas respectively. A total of eight such positions would be available, but only three would be filled. The Ca ion is small enough to fit in the hexagons of SiO_4 tetrahedra, as in margarite. Since some OH would be replaced by O coordinate valencies would be balanced.

This possible explanation must be considered merely as a suggestion to be followed, if future analyses of chlorites show similar discrepancies. If they are small as those of the chlorite from Burra Burra, Tenn. (Table 3), other explanations, like random interstratifications of occasional heavy talc units with chlorite units, might possibly be called upon. In the case of the Trumbull mineral this would not be a plausible explanation.

TABLE 4. ANALYSES, IONIC DISTRIBUTION, AND DENSITIES OF PROCHLORITE FROM TRUMBULL, CONN. E. V. SHANNON, *analyst.*

	1	2	3	4	5	6	7
		M. R.	+ ions	+ charges	Adj. + ions	Adj. + charges	Adj. anions
SiO_2	23.69	.3944	18.75	75.0	19.4	77.6	O 92
TiO_2	tr.						
Al_2O_3	21.26	.2086	19.82	59.4	20.7	62.1	
FeO	26.52	.3692	17.55	35.1	18.3	36.6	
CaO	3.32	.0592	2.81	5.6	2.9	5.8	
MnO	.43	.0061	.29	0.6	0.3	.6	
MgO	17.60	.4365	20.75	41.5	21.7	43.4	
Total			79.97	217.2	83.3	226.1	
			(OH)		(OH)		
H_2O+	7.63	.4234	40.26		42.1		(OH) 42
Total	100.45						134
Mol. Weight			4776		4993		
Theor. Density			2.812		2.942		
Obs. Density					2.944		

CONCLUSIONS

Amesite has the formula $(OH)_8(Mg, Fe)_4Al_2(Si_2Al_2)O_{10}$ and, contrary to earlier opinions, has a structure which is more like that of kaolinite than that of chlorite. It differs from a true kaolinite structure in this, that a chlorite unit is interlayered with kaolinite units in the ratio of about one 14 Å chlorite unit to between 10 to 16 kaolinite units each 7 Å high. This results in a superlattice of considerable dimensions along the *c* axis. This interstratification is probably essential to keep the kaolinite units from curving.

There is a considerable shrinkage normal to 001 in amesite when compared to true kaolinite or to regular chlorites. It can be shown that such shrinkage, which also occurs in the chlorites, is connected with a substitution of Al for Si in the tetrahedral layers. Increase in this substitution causes decrease in the length of the *c* axis. Finally, when the limiting case of amesite is reached, the chlorite structure becomes unstable for reasons stated above. The same holds true for the mineral cronstedtite, which also has a kaolinite structure, in which about half of the Si has been replaced by Fe'''.

A discrepancy in the theoretical and observed densities of chlorites, particularly in prochlorite from Trumbull, Conn., suggests that more ions are in the structure than are ordinarily thought possible. A place for these additional cations may possibly be found in the centers of the hexagonal rings of SiO_4 tetrahedra, that is, in positions similar to Ca in brittle mica.

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THE CRYSTAL STRUCTURE OF α-SiC, TYPE IV

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ABSTRACT

A new modification of α-SiC, designated as type IV by Thibault, was found by him to have a rhombohedral unit cell, with $a_r = 17.68$Å and $\alpha = 9°58'$; space group $R3m$; $Z = 7$. For comparison with the hexagonal types, the rhombohedral unit can be referred to hexagonal axes, with $a_0 = 3.073$Å and $c_0 = 52.78$Å. This unit contains 21 formula weights.

There are shown to be only five possible atomic arrangements compatible with the rhombohedral space group and with the assumption that each Si atom is surrounded tetrahedrally by 4 C atoms, and each C atom by 4 Si atoms. Of these five arrangements, only one gives satisfactory agreement between the observed and the calculated intensities. This arrangement, referred to hexagonal axes, is as follows:

7 Si at 000, 0 0 $4z$, 0 0 $6z$, 0 0 $9z$, 0 0 $12z$, 0 0 $15z$, 0 0 $17z$.
7 C at 00p, 0 0 $4z+p$, 0 0 $6z+p$, 0 0 $9z+p$, 0 0 $12z+p$, 0 0 $15z+p$, 0 0 $17z+p$.
7 Si and 7 C at 2/3 1/3 1/3+the above coordinates.
7 Si and 7 C at 1/3 2/3 2/3+the above coordinates.
$z = 1/21$, $p = 1/28$.

INTRODUCTION

The existence of five crystalline modifications of SiC has been known for some time. These five include one which is cubic, two which have hexagonal symmetry, and two with trigonal symmetry. Various studies of these modifications and their crystal structures have been made.[1] The cubic form has a β-ZnS type of structure, with each silicon atom surrounded tetrahedrally by four carbon atoms, and each carbon by four silicon. This same basic arrangement is found in all of the other modifications. In the two hexagonal types, all atoms lie on the vertical symmetry axes through the points A, B and C, which have the coordinates 000, 2/3 1/3 0 and 1/3 2/3 0, respectively (Fig. 1). It will be necessary to make frequent reference to these symmetry axes, and in the following discussion they will be designated simply as A, B and C. The two hexagonal types differ from each other in the number and sequence of atoms along A, B and C. The hexagonal symmetry is such that the arrangements along the trigonal axes B and C are identical, but differ from that along A. The two types with trigonal symmetry are based on rhombohedral unit cells. The sequence of atoms along A, beginning at 000, must be identical with the sequences along B and C, beginning at 2/3 1/3 1/3 and 1/3 2/3 2/3, respectively, since all three axes are alike.

In a comprehensive study of SiC, Thibault[2] has proved the existence of two additional types, both with rhombohedral unit cells. Contrary to previous usage, Thibault calls the cubic form β-SiC (isostructural with β-ZnS) rather than SiC, type IV. All the remaining forms, both hexagonal and trigonal, are called α-SiC, each one being designated by a type number. Thibault calls the two new modifications of α-SiC types IV and VI, leaving types I, II, III and V as originally designated by Ott. This usage is followed in the present paper.

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[1] For a complete summary and list of references see the paper by Thibault in the preceeding issue of this Journal, pages 327–362.

[2] Thibault, N. W. Morphological and structural crystallography of SiC: *Am. Mineral.*, **29**, 249–278; 327–362 (1944).

No crystallographic data have been published for type V, but for the remaining α-SiC types, Thibault has shown the very remarkable morphological relationships, involving axial ratios which are multiples of a common fundamental unit, and characteristic form series for each type. Moreover, he established a complete correlation between the crystallographic data and the unit cells. However, no attempt was made by Thibault to determine the actual atomic arrangements for either type IV or type VI.

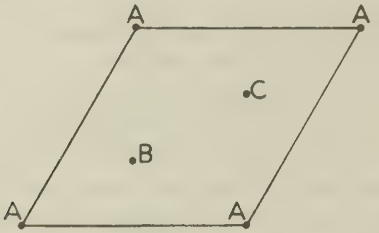

Fig. 1. Basal projection of hexagonal unit cell, showing the vertical symmetry axes *A*, *B*, and *C*.

In the course of this investigation of the crystal structure of type IV, the author needed several Weissenberg photographs, and he is greatly indebted to Dr. Thibault for the use of the crystal on which the type was established.[3]

STRUCTURE OF α-SiC, TYPE IV

The data obtained by Thibault from the morphology, etch figures and *x*-ray study of type IV point unequivocally to a rhombohedral unit cell, with the space group $R3m$. Referred to hexagonal axes, the unit cell was found to have dimensions as follows: $a = 3.073$Å and $c = 52.78$Å. This cell is twenty one layers high. Because of the very definite interrelationship with the other types, it seems very certain that the same basic tetrahedral arrangement of silicon and carbon atoms must be present. If this is the case, the new type differs from the others solely in the manner in which successive layers of the structure are oriented with respect

[3] A report on the crystal structure of type VI is expected to appear in this Journal in the near future.

to each other, or in the sequence of the atoms along the vertical directions *A*, *B* and *C* (Fig. 1).

If a silicon atom is on *A*, with the coordinates 000, then a carbon atom must be directly above it at $00p$. The Si–C distance common to all of the types is 1.90 Å, which combined with the length of the *c* axis in type IV, gives a value of 1/28 for the vertical parameter p. In the next higher silicon layer, there are 2 equivalent positions, each equally probable, i.e., on *B* at 2/3 1/3 z, or on *C* at 1/3 2/3 z. Since there are twenty one layers of silicon atoms in the unit cell, the parameter z has a value of 1/21. If we arbitrarily choose the first of these two possibilities, on *B*, there would then have to be a carbon atom directly above it, at 2/3 1/3 $z+p$. In the third layer of silicon atoms, there would again be two choices, on *C* or *A*, with the vertical parameter equal to $2z$. This dichotomous relationship for each successive layer of silicon atoms would continue throughout the entire length of the unit cell. All silicon and carbon atoms would lie only on *A*, *B* and *C*, and would have vertical parameters involving only nz and $nz+p$, respectively. There would be 7 silicon and 7 carbon atoms on each of the vertical axes *A*, *B* and *C*, but no two could be occupied at the same horizontal level. It is evident that the carbon atoms would have an arrangement identical with that of the silicon atoms, only displaced a distance p in the vertical direction. Consequently, in discussing the atomic arrangement, it will be much simpler to refer in most cases only to the silicon atoms, keeping in mind the fact that above each silicon there must be a carbon atom.

There are two very definite restrictions controlling the sequence of silicon atoms along any one of the vertical directions *A*, *B* or *C*. First, the tetrahedral arrangement does not permit any two successive layers to be occupied along the same axis—the interval must be two or more. Second, the rhombohedral lattice requires that for any atom at nz on *A*, there must also be one at $1/3+nz$ on *B*, and one at $2/3+nz$ on *C*. Thus placing a silicon atom at 000 on *A* automatically places one on *B* at 2/3 1/3 $7z$, and another on *C* at 1/3 2/3 $14z$ ($7z=7/21=1/3$; $14z=14/21=2/3$). In more general terms this means that the interval between any two silicon atoms on *A*, *B* or *C* cannot be $7z$ or $14z$. The combined effect of these two restrictions is that the intervals between silicon atoms along *A*, *B* and *C* cannot be 1, 7 or 14, or any combination which adds up to 7 or 14, such as 5+2, 4+3 or 6+4+4.

The determination of all the possible sequences along *A*, *B* or *C* which are compatible with these restrictions is easily carried out by a method used by Ott in his determination of the structure of type I.[4] In the following tabulation the numbers from 0 to 20 represent the 21 succes-

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[4] Ott, H., Das Gitter des Karborunds: Zeits. Krist., **62,** 201–217 (1925).

0	(1)	2	3	4	5	6
(7)	8	9	10	11	12	13
(14)	15	16	17	18	19	(20)

sive silicon layers in the unit cell. If we arbitrarily place a silicon atom on *A* at 0, there cannot also be one on *A* at 1 (next layer above) or at 20 (next layer below). Neither can there be one on *A* at 7 or 14, for the rhombohedral lattice requires that *B* and *C* be occupied at these levels. Accordingly, if we always start the sequence on *A* at 0, we do not need the numbers 1, 7, 14 and 20 in the table No two numbers may be chosen for *A* from any one vertical column of the table, for they would be separated by intervals of 7 or 14. Since there are 7 silicon atoms to be placed on *A*, one number must be chosen from each of the seven vertical columns. But no two successive numbers may be chosen from the same horizontal row. Following these rules, a possible sequence could be 0 8 2 17 4 12 6, or in ascending order, 0 2 4 6 8 12 17 0. A total of 43 such sequences can be derived. Two additional sets of 43 may be obtained by starting the sequences with 7 and 14, but these are exactly congruent with the original 43, and need not be considered. Of the 43 sequences, many are duplicates, either being the same sequence in reverse order, or differing only in the starting point of the sequence. For example, the sequence 0 2 6 11 15 17 19 0 has *intervals* between successive numbers of 2 4 5 4 2 2 2, and therefore is equivalent to the first sequence above, where the *intervals* are 2 2 2 2 4 5 4. It is the intervals which are the distinguishing feature. Of the 43 possible sequences, there are only 6 different series of intervals, as follows:

(1)	3	3	3	3	3	3	3
(2)	2	2	2	9	2	2	2
(3)	2	2	2	6	3	2	4
(4)	3	2	3	5	3	2	3
(5)	2	2	4	5	4	2	2
(6)	4	2	3	3	3	2	4

It will be noticed that the number 1 does not appear, and there are no groups of adjacent numbers such as 43, 223, 52, 644 and 8222, which add up to 7 or 14. Such forbidden combinations were all eliminated by the method used.

The above 6 sequences are all compatible both with the basic tetrahedral arrangement and with the rhombohedral lattice. However, the first one is not acceptable for type IV. It would consist merely of the repetition of an identical structure seven times in the direction of the *c* axis. The true unit would be only three layers high, and in fact would correspond to the structure of the cubic β-SiC, treated as a rhombo-

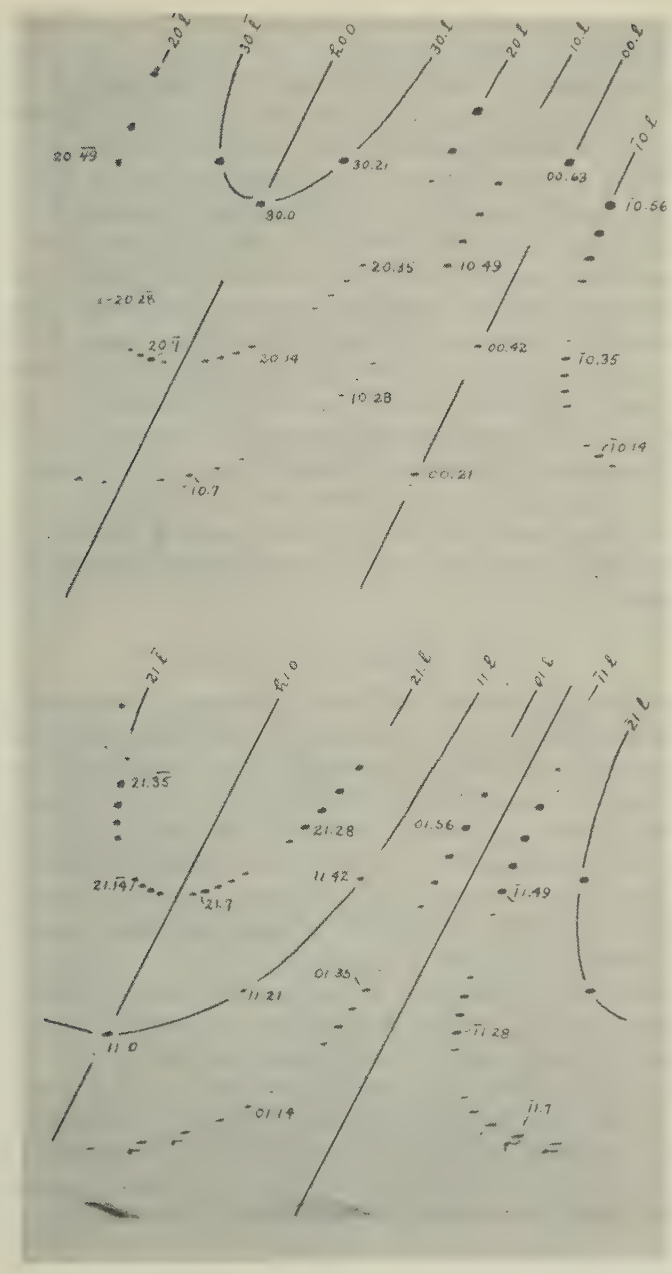

FIG. 2. Weissenberg photographs of α-SiC, type IV; *a*-axis rotation. Above—zero level; below—first level.

hedron by making one of the cube diagonals the *c* axis. The remaining five sequences all have equal geometrical probabilities. The only apriori grounds for making a choice would be from the standpoint of structural uniformity. It could be argued that it would be highly improbable for silicon atoms to be distributed regularly along *A* at intervals of two, and then have the interval jump to nine, as in sequence (2). In his structure determinations of types I, II and III, Ott found intervals of 2, 3 and 4 only. Thus for the rhombohedral type I, with 15 layers, Ott[5] deduced three possible sequences: 33333, 22722 and 24342. The first was eliminated for a reason similar to that indicated for 3333333 above. The second sequence did not give proper calculated intensities, while the last one gave excellent agreement between calculated and observed intensities.

If we make the assumption here that only intervals of 2, 3 and 4 are possible, this would immediately eliminate the sequences (2), (3), (4) and (5), leaving only (6), 4233324. To test the validity of this assumption, intensity calculations have been carried out for all five sequences. The results are shown graphically in Figs. 3 and 4, and will be discussed later. They show quite clearly that only the final sequence 4233324 gives calculated intensities which are in satisfactory agreement with the observed intensities.

CALCULATION OF INTENSITIES

The general structure factor for the space group *R3m* is rather complex,[6] but fortunately a very simplified form is possible in this case. On the Weissenberg films (Fig. 2) there are extensive series of reflections from trigonal and ditrigonal pyramidal planes. These include the $10 \cdot l$ series with 41 reflections, the $20 \cdot l$ series with 36, and the $21 \cdot l$ series with 26 reflections. This large number is ample for the structure determination, and for these particular series the structure factor can be expressed in a very simple form. For example, the $10 \cdot l$ planes all lie in a common zone, and the position of any atom with respect to any $10 \cdot l$ plane can be completely expressed by the term $2\pi(hx'+lz)$, where h and l are the Bravais-Miller indices, and x' and z are rectangular coordinates of the atom, with x' measured along the intermediate (b) axis and having only the values of 0, 1/3 and 2/3, while z is the usual vertical coordinate. Further simplification results because, although a hexagonal cell is being used for the description, the lattice is actually rhombohedral. Consequently, a given atom in the sequence on *A* has exactly the same position with respect to those planes which can reflect in a rhombohedral lattice as do the equiva-

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[5] Ott, H., *loc. cit.*

[6] *Inter. Structure Tables*, p. 242.

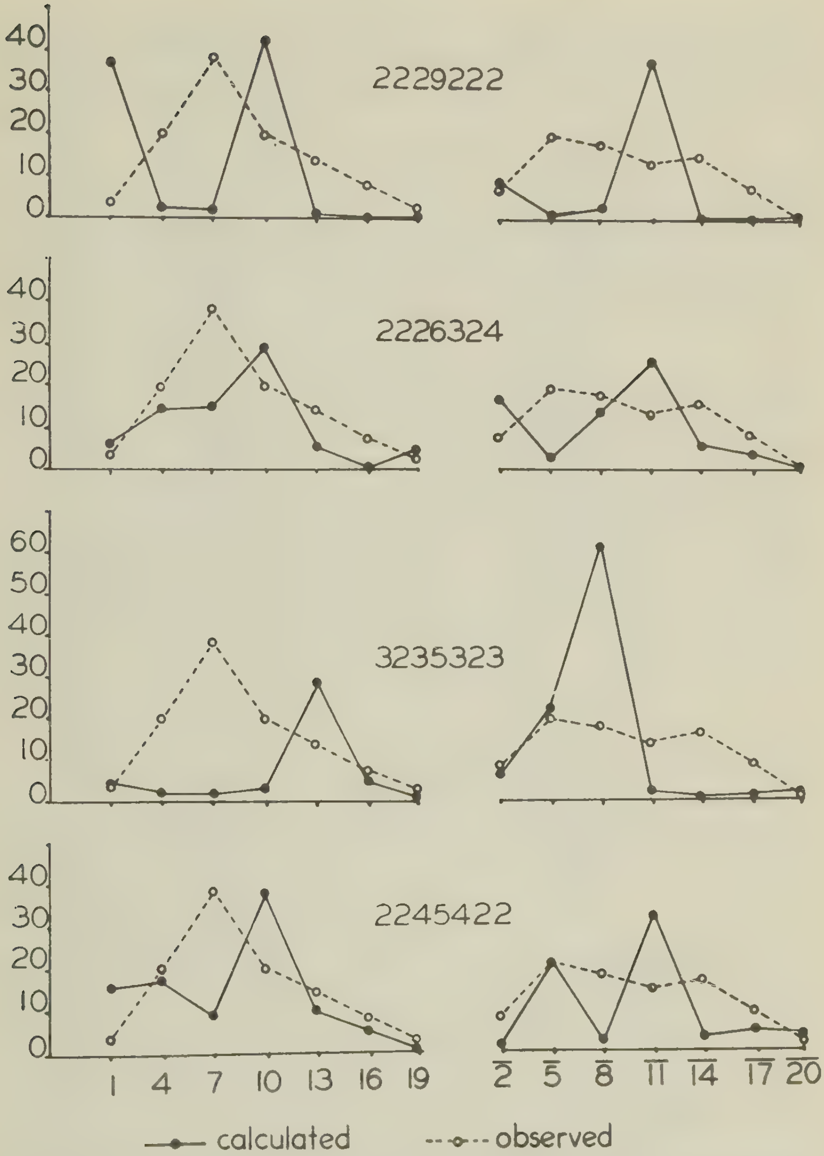


FIG. 3. Observed intensities compared with the calculated intensities for a portion of the $10 \cdot l$ series of reflections from α-SiC, type IV, for the four discarded sequences. Relative intensities are plotted vertically, and values of l are plotted horizontally.

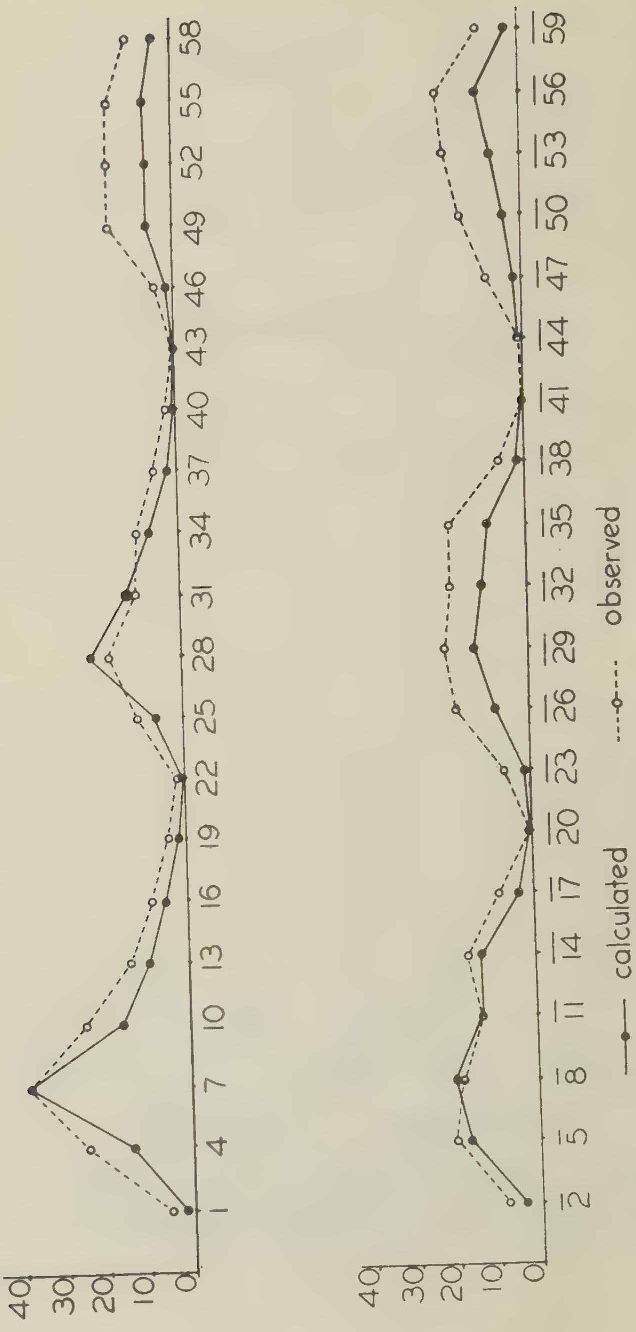


FIG. 4. Observed intensities compared with the calculated intensities for the entire series of $10\cdot l$ reflections from α-SiC, type IV, for the sequence 4233324.

lent atoms on B and C. Hence instead of three terms involving the three values of x', only one term need be used. If the value $x'=0$ be chosen, hx' drops out, and the term reduces to $2\pi(lz)$. The intensity formula then becomes

$$I \propto [\Sigma f_0\mathrm{Si} \cos 2\pi(lz) + \Sigma f_0\mathrm{C} \cos 2\pi(lz+p)]^2 + [\Sigma f_0\mathrm{Si} \sin 2\pi(lz) + \Sigma f_0\mathrm{C} \sin 2\pi(lz+p)]^2.$$

The summation must include the seven values of z for silicon, and the seven values of $z+p$ for carbon. Four of the five sequences for the silicon atoms are symmetrical, and for these the sine term is 0. Both the sine and cosine terms must be used for the unsymmetrical silicon sequence, and for all of the carbon atom sequences.

A similar situation is encountered in the series $20\cdot l$ and $21\cdot l$. In fact the trigonometrical portion of the formula is identical for planes with the same value of l, such as $10\cdot 1$, $20\cdot\bar{1}$ and $21\cdot 1$, or $10\cdot\bar{2}$, $20\cdot 2$ and $21\cdot\bar{2}$. The only difference is in the changed values of f_0 and of the correction factor. A comparison of the intensities for these three series of reflections on the Weissenberg films shows this similarity very clearly (Fig. 2). Not only are the three series very much alike, but variations in intensity tend to be repeated in each series. The contributions of the silicon atoms to the various reflections with l values from 1 to 20 are repeated in reverse order from 22 to 41, and then again directly from 43 to 62. Since the reflecting power of silicon is considerably greater than that of carbon, this repetition is impressed upon the series.

Because of this repetition, the calculated intensities for all sequences except the correct one (4233324) are shown only for values of l from 1 to 20 for the $10\cdot l$ series. For the sequence found to be correct, they are shown for the complete $10\cdot l$ series as recorded on the film, but are omitted for the $20\cdot l$ and $21\cdot l$ series, since these latter, although confirmatory, provide no additional information.

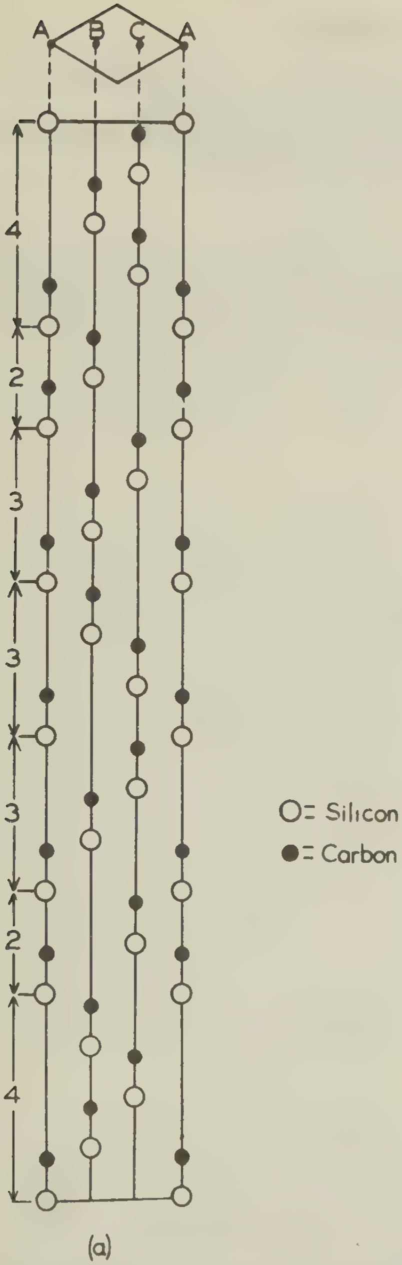
The numerical values plotted in Figs. 3 and 4 for the calculated intensities are derived from the formula by inserting the appropriate values of lz and p, and of f_0 for silicon and carbon, and then applying the Lorenz and polarization correction, $1+\cos^2 2\theta/\sin 2\theta$. The highest value thus obtained was 38,000 for the $10\cdot 7$ reflection. This is plotted as 38 in Figs. 3 and 4, and all other calculated values are reduced proportionally. Likewise, the strongest reflection on the film, also $10\cdot 7$, has arbitrarily been given an estimated intensity of 38. On films with normal exposures, quite a number of spots have received exposures more than sufficient to develop maximum blackness, and hence appear of nearly equal intensity. To differentiate between these, a series of graduated exposures was made, varying from 4 hours to 20 minutes. From these films the relative intensities of the various reflections could be estimated more accurately. The β-reflections on the normal exposures of 0-level films can also be used in some cases to differentiate between planes whose α-reflections appear of equal intensity. Because of the irregular shape of the crystal, absorption effects are variable, and corresponding spots on different films may show some discrepancies in apparent intensities. In such cases an attempt has been made to use an averaged value for the estimated intensity. The most accurate intensity comparisons can be made on reflections adjacent to one another on the films, so the data have been divided into two sets, $10\cdot l$ and $10\cdot\bar{l}$.

As seen is Fig. 3, there are marked disagreements between the calculated and observed intensities for the discarded sequences, while Fig. 4 shows the very satisfactory agreement for the accepted sequence 4233324. The observed intensities of the back reflections (high θ) are distinctly greater than the calculated values, but this is to be expected, since no correction for absorption was applied. The magnitude of this over-emphasis of back reflections can be seen by a comparison of the three orders of reflections from a single plane—$10\cdot 7$, $20\cdot 14$ and $30\cdot 21$ (Fig. 2). The calculated intensities for these three reflections are in the ratio of 38:9:8, while the observed intensity of $30\cdot 21$ is distinctly greater than that of $20\cdot 14$.

THE STRUCTURE OF α-SiC, TYPE IV

In order to obtain the structure indicated by the correct sequence, 4233324, it is only necessary to place 7 silicon atoms along *A* at heights corresponding to the sequence, namely, at 0, 4/21, 6/21, 9/21, 12/21, 15/21, and 17/21. A similar set of 7 silicon atoms is placed on *B*, beginning the sequence at a height of 1/3, and another similar set along *C*, beginning at a height of 2/3. One carbon atom is placed above each of the 21 silicon atoms at a distance $p = 1/28$. This is illustrated in Fig. 5a.

The rhombohedral arrangement is shown in Fig. 5b. This unit contains only 7 formula weights, and the distribution of Si and C atoms corresponds to that along *A* in the hexagonal unit.



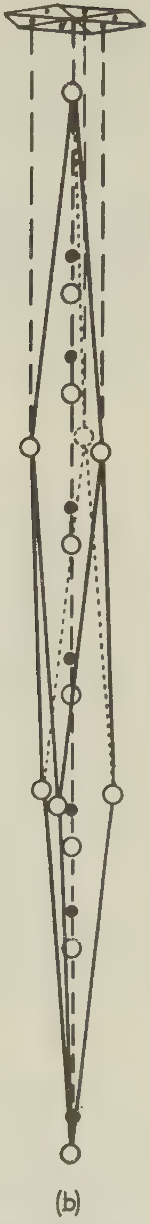


FIG. 5*a*. Vertical section along the (11 · 0) plane of the hexagonal unit cell of α-SiC, type IV.

FIG. 5*b*. Corresponding rhombohedral unit cell of α-SiC, type IV.

The atomic positions are as follows:

Hexagonal unit cell:

7 Si at 000, 0 0 $4z$, 0 0 $6z$, 0 0 $9z$, 0 0 $12z$, 0 0 $15z$, 0 0 $17z$.

7 C at 00p, 0 0 $4z+p$, 0 0 $6z+p$, 0 0 $9z+p$, 0 0 $12z+p$, 0 0 $15z+p$, 0 0 $17z+p$.

7 Si and 7 C at 2/3 1/3 1/3+the above coordinates.

7 Si and 7C at 1/3 2/3 2/3+the above coordinates.

Rhombohedral unit cell:

7 Si at 000; $4z$, $4z$, $4z$; $6z$, $6z$, $6z$; $9z$, $9z$, $9z$; $12z$, $12z$, $12z$; $15z$, $15z$, $15z$; $17z$, $17z$, $17z$.

7 C at ppp; $4z+p$, $4z+p$, $4z+p$; $6z+p$, $6z+p$, $6z+p$; $9z+p$, $9z+p$, $9z+p$; $12z+p$, $12z+p$, $12z+p$; $15z+p$, $15z+p$, $15z+p$; $17z+p$, $17z+p$, $17z+p$.

For both unit cells $z=1/21$, $p=1/28$.

POLLUCITE FROM KARIBIB, SOUTH WEST AFRICA*

H. J. NEL, *Geological Survey of the Union of South Africa, Pretoria, South Africa.*

ABSTRACT

Pollucite, the only caesium silicate mineral known, is recorded from a new locality. It has a refractive index of 1.5173 (Na light) and the dispersion $n_F - n_C = .0083$. A chemical analysis of the mineral is given and from a consideration of this and other available analyses, it appears that an isomorphous series exists between pollucite and analcite. This series results from the isomorphous replacement of Cs^+ by Na^+ with the concomitant introduction of a water molecule into the unit cell. The variation of the refractive index within this series is shown graphically. Some dehydration results obtained on the pollucite from Karibib are briefly discussed.

INTRODUCTION

The first known occurrence of pollucite in Southern Africa came to light recently when a specimen submitted to the Geological Survey by Mr. F. J. Jooste† was found to consist mainly of this mineral. According to Mr. Jooste the pollucite, of which he considered some twenty-five tons to be available, was discovered on the farm Okongava Ost No. 72, approximately seven miles S.S.E. of the town of Karibib in South West Africa. Subsequently further prospecting work was done, though it is not known whether additional tonnages have been proved.

The pollucite is associated with lithium minerals in pegmatites, thus once again illustrating its characteristic paragenesis. De Kock (1), who described the lepidolite deposits of the Karibib area in 1932, found the more important of them to be grouped on and around the farm Okongava Ost No. 72. In addition to lepidolite, petalite and amblygonite are found here in exploitable quantities.

Because of pressure of work it has not been found possible to visit these deposits, so that the present paper will necessarily be confined to a description of the mineralogical and chemical properties of the pollucite.

MINERALOGY

The massive pollucite from Karibib is traversed by numerous thin white veins up to a millimetre in thickness. These veins are composed mainly of an extremely fine-grained clay-like mineral which is anisotropic with $n = 1.55$–1.56. Veins of lepidolite of the order of 4 millimetres thick and some quartz are also present in the pollucite available for study.

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* Published by permission of the Hon. the Minister for Mines.

† Managing Director, Jooste Lithium Mines (Pty.) Ltd., Karibib, South West Africa.

Physical Properties

The pollucite is perfectly colorless, glassy clear and fully isotropic. The refractive index, determined by measuring the angle of minimum deviation on a small prism specially prepared for the purpose, is 1.5173 ±.0002 (Na light). The dispersion, similarly obtained, is given graphically in Fig. 1. The specific gravity, determined by suspension of pure fragments of pollucite in a solution of bromoform and alcohol, was found to be 2.865±.005.

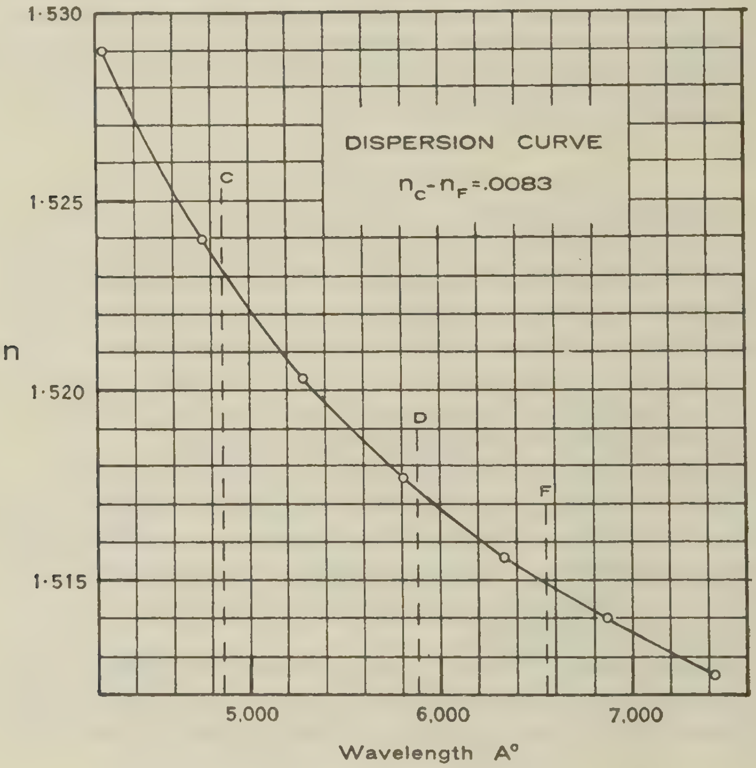

Fig. 1. Dispersion curve of pollucite from Karibib, S. W. A.

Chemical Composition

For analytical purposes pure fragments of pollucite were selected from crushed material under a binocular microscope. In this way pollucite of ideal purity was obtained.

A qualitative spectrographic analysis of the pollucite by Dr. B. Wasserstein of the Geological Survey yielded the following results:—

Present: *Cs*, *Na*, *Al*, *Si*, *Rb*, *Tl*, K
Trace: *Li*, Ga.
Absent: Sr, Ca, Mg, Mn, Fe, F, B, Ti, V, Cr, Pb.

The chemical analysis given in Table 1 was done by Dr. C. F. J. van der Walt of the Division of Chemical Services, Pretoria. The micromethod employed by him to determine Cs_2O and Rb_2O+K_2O is based on a method described in "The Analysis of Minerals and Ores of the Rarer Elements" (2nd Ed.) by W. R. Schoeller and A. R. Powell (Griffin and Co. Ltd., London. 1940).

TABLE 1

a		b	c		d	e	
SiO_2	45.7	.7608	Si	.7608	33.39	SiO_2	46.4
Al_2O_3	17.2	.1688	Al	.3376	14.81	Al_2O_3	16.3
Cs_2O	30.2	.1073	Cs+Rb+K	.2286	10.03	Cs_2O	32.0
Rb_2O+K_2O*	1.3	.0070	Na	.0904	3.97	Na_2O	2.8
Na_2O	2.8	.0452	O	2.1875	96.00	H_2O	2.5
H_2O	2.66	.1477	H	.2954	11.69		
							100.0
Total	99.86						

* Calculated as Rb_2O

a. Chemical analysis by C. F. J. van der Walt.
b. Molecular proportions.
c. Atomic proportions.
d. Calculation of formula on a water-free basis of O=96.
e. Theoretical composition for pollucite with the unit cell $Cs_{10}Na_4Al_{14}Si_{34}O_{96}\cdot 6H_2O$.

The crystal structure of pollucite has been investigated by Strunz (2) and Náray-Szabó (3), and it appears to be accepted that the unit cell contains 96 atoms of O (water-free basis) and that $Si+Al=48$. In the ideal case $2Al=Si$, though to what extent the actual formulae may depart from the theoretical as far as this consideration is concerned, will be shown later. The unit cell formula for the pollucite from Karibib, calculated from the analysis on the basis of $O=96$, is as follows:

$$Cs_{10}Na_4Al_{14}Si_{34}O_{96}\cdot 6H_2O$$

THE RELATIONSHIP OF ANALCITE AND POLLUCITE

Various authors have commented on the similarity of pollucite and analcite. The unit cell of analcite has the symmetry of the space group O_h^{10}(7, 15), and that of pollucite $O_h^{10}-Ia3d$ or $D_{4h}^{20}-I4/acd$(2, 3). The respective sizes of the unit cells are to all intents and purposes similar, viz. pollucite $a_0=13.64-13.74$ Å (2, 3, 4, 5, 6) and analcite $a_0=13.68$ Å (7).

The unit cell formula for analcite is $Na_{16}Al_{16}Si_{32}O_{96}\cdot 16H_2O$ and that of "ideal" pollucite has been given by Strunz (2) as $Cs_{16}Al_{16}Si_{32}O_{96}\cdot 8H_2O$. It will be shown in the following pages however, that the unit cell of sodium-free pollucite should not contain any water.

The crystal structure of pollucite has been investigated by Strunz (2) and Náray—Szabó (3, 12) and that of analcite notably by Taylor (7, 11). Both minerals are built up of alumina and silica tetrahedra conforming to the silica type, though there is some difference of opinion regarding the positions occupied by the alkali ions. According to Náray-Szabó (3) pollucite and analcite have the same Al-Si-O frameworks: in pollucite the caesium and in analcite the sodium ions occupy the 16-fold positions $(\frac{1}{8}\frac{1}{8}\frac{1}{8})$ etc., while the water molecules partially occupy the 24-fold positions $(0\frac{1}{4}\frac{1}{8})$ etc. Taylor, however, maintains that in analcite the 16 sodium ions are distributed at random over the 24-fold positions $(0\ \frac{1}{4}\ \frac{1}{8})$ etc., and the water molecules occupy the 16-fold positions $(\frac{1}{8}\ \frac{1}{8}\ \frac{1}{8})$ etc.

In the past investigations have not indicated Cs and Na separately in the formulae for pollucite, thereby missing a rather interesting relationship. The pollucite analyses which were available in 1938 are quoted by Quensel (8). Three later analyses are given by Richmond and Gonyer (5). These analyses may be consulted by referring to the two above mentioned publications.

The unit cell formulae given below were calculated from some of these analyses on the water-free basis of $O=96$ and adjusted slightly in some instances to satisfy the condition $Al+Si=48$. In this case it may readily be seen that $Cs+Na$ must be equal to the number of Al atoms given in the unit cell formula, so as to satisfy the valencies. Here $Cs+Ca+K+Mg+Rb$ is given as Cs, $Na+Li$ as Na and in a few instances $Al+Fe$ as Al. It may be as well to mention that in these chemical analyses CaO, MgO, K_2O, Fe_2O_3 and Li_2O are occasionally present only in very small amounts, usually well below 0.5% each. The presence of these elements in some cases may probably be ascribed to impurities present in the pollucite analyzed.

For the unit cell formulae given below only analyses were used where the original references could be consulted:

	Localities
A. $Cs_{12}Na_3Al_{15}Si_{33}O_{96}\cdot 4H_2O$.	i. Tamminen Quarry, Greenwood, Maine (5).
	ii. Rumford, Maine (13).
	iii. Hebron, Maine (14).
B. $Cs_{11}Na_4Al_{15}Si_{33}O_{96}\cdot 5H_2O$	i. Leominster, Massachusetts. (5)
C. $Cs_{11}Na_3Al_{14}Si_{34}O_{96}\cdot 5H_2O$	ii. Varutråsk, Sweden (8).
D. $Cs_{10}Na_4Al_{14}Si_{34}O_{96}\cdot 6H_2O$	i. Karibib, South West Africa.
	ii. Elba (6).
E. $Cs_7Na_7Al_{14}Si_{34}O_{96}\cdot 9H_2O$	i. Oxford Milling and Mining Co. Quarry, Greenwood, Maine (5).

In some instances a formula slightly modified from that given above would also satisfy the relevant analyses sufficiently well to be accepted. This is, however, of secondary importance as these alternative formulae would do equally well to illustrate the relationship between analcite and pollucite.

From these formulae the following relationships may be deduced:

1. The number of Cs ions is inversely proportional to the number of Na ions in the unit cell.
2. $Cs^+ + H_2O = 16$.

In view of the importance of the second relationship, it may be as well to give the actual values obtained (Table 2) in calculating the unit cell formulae. The total of $Cs^+ + H_2O$ is considered to be constant at 16 within the range of experimental error.

TABLE 2

	A			B	C	D		E
	i	ii	iii	i	i	i	ii	i
Cs	11.66	11.99	12.41	11.00	10.81	10.03	10.90	7.38
H_2O	4.09	3.98	3.82	5.03	4.31	5.85	6.54	8.69
Total	15.75	15.97	16.23	16.03	15.12	15.88	17.44	16.07

(In the case of formula D ii, the analysis shows 0.72% CaO and 0.77% Fe_2O_3. This total shows the greatest deviation from the average total of 16.)

From the formulae it will be seen that when one sodium ion replaces one caesium ion, there is a concomitant introduction of a molecule of water into the unit cell. It is interesting to note that the replacement suggested here involves two ions whose ionic radii are by no means comparable: that of Cs^+ is 1.65 Å, while that of Na^+ is 0.98 Å (Goldschmidt). The most obvious explanation for this unique type of replacement would be that when Na^+ is substituted for Cs^+, "free" space would be left by the latter which would facilitate or permit the introduction of a water molecule into the unit cell. In this case the structure for pollucite and analcite as proposed by Náray-Szabó would appear to be more acceptable than that advanced by Taylor.

Thus an isomorphous series, at least of limited miscibility, exists between analcite and pollucite, and is effected by the isomorphous replacement of Cs^+ by Na^+, with the accompanying introduction of a water molecule. The miscibility of pollucite and analicite is thought to depend more on the composition of the mineralizing solutions at the time of formation, rather than on any inherent characteristics of the respective unit cells.

Omitting for the purpose any replacement affecting the Al and Si ions, theoretical end members of the series, with idealized unit cell formulae as follows, are obtained.

Pollucite	$Cs_{16}Al_{16}Si_{32}O_{96}$.
Analcite	$Na_{16}Al_{16}Si_{32}O_{96} \cdot 16H_2O$

Thus it will be seen that the unit cell of sodium-free pollucite should not contain any water, and that it is therefore not a zeolitic mineral. With analcite which is a typical zeolite, it forms a series which becomes progressively more zeolitic as the analcite end of the series is approached. The series may be represented by the following generalized theoretical formula where $x=0$ in pollucite and $x=16$ in analcite

$$Cs_{16-x}Na_xAl_{16}Si_{32}O_{96} \cdot xH_2O \qquad \text{(i)}$$

The Replacement Affecting the Al and Si ions

In the determination of the replacement affecting the Al and Si ions, formula *A* may be taken as an example:

$$Cs_{12}Na_3Al_{15}Si_{33}O_{96} \cdot 4H_2O \qquad \text{(ii)}$$

and compared with the nearest theoretical formulae (see i)

$$Cs_{12}Na_4Al_{16}Si_{32}O_{96} \cdot 4H_2O \qquad \text{(iii)}$$
$$Cs_{13}Na_3Al_{16}Si_{32}O_{96} \cdot 3H_2O \qquad \text{(iv)}$$

The following replacements may therefore be considered to have taken place:

(ii) and (iii) $1Al^{3+}+1Na^+$ by Si^{4+}
(ii) and (iv) $1Al^{3+}+1Cs^+$ by $1Si^{4+}+1H_2O$.

Similarly in formulae *C*, *D* and *E*

$2Al^{3+}+2Na^+$ by $2Si^{4+}$
or $2Al^{3+}+2Cs^+$ by $2Si^{4+}+2H_2O$.

It is interesting to note that the reverse replacements to those indicated above do not take place. This is in agreement with the conception of ionic replacement according to comparable ionic radii.

A generalized formula for the analcite-pollucite series, taking these replacements into consideration, may be written as follows:

$$Cs_{16-x}Na_{x-y}Al_{16-y}Si_{32+y}O_{96} \cdot xH_2O \qquad \text{(v)}$$

where $x=0$ and $y=0$ for the theoretical end-member pollucite.

When $x=16$ and $y=0$ the ideal analcite formula is obtained. As can be seen from the formulae, y is either 1 or 2, and in ideal analcite and pollucite equal to zero.

Richmond and Gonyer (5) proposed the formula $Cs_{14+x}Al_{14}(Al_xSi)_{34}O_{96} \cdot 4-9H_2O$ for pollucite. Here $x=0$, 1 or 2. As this formula fails to express the relationship of Cs^+ to Na^+ and H_2O, formula (v) should be more acceptable.

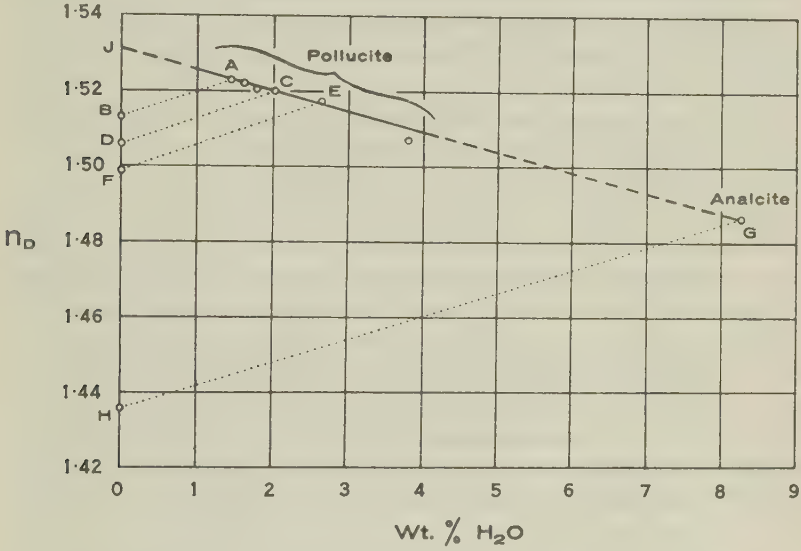

FIG. 2. Variation of the refractive index in the pollucite-analcite series.

In Fig. 2 the variation of the refractive index with the water content of the pollucite-analcite series is shown by means of the graph *JG*, where *J* represents the interpolated refractive index (1.532) of water-free and sodium-free pollucite. The point *G* represents pure analcite. Fleischer and Ksanda (9) and Strunz (2) have shown that the refractive index of pollucite is lowered on dehydration. The dotted lines *AB*, *CD*, *EF* and *GH* represent the changes undergone by the refractive indices of pollucite from Hebron (9), Elba (9) and South West Africa and that of analcite (Fassathal, Tyrol) on dehydration. For the loss of every 1.46% H_2O in pollucite and 1.66% H_2O in analcite, n_D is lowered by 0.01.

THE DEHYDRATION OF POLLUCITE

This subject was studied carefully by Fleischer and Ksanda (9) who came to the conclusion that "the shape of the dehydration curve is not, in this case at least, a reliable means of deciding the role of water in a mineral." From other considerations, such as the similarity of the rotation powder spectrum photographs of natural and dehydrated pollucite, the difficulty of dehydration and rehydration, the latter even under high temperatures and pressures, led these authors to the conclusion that the water present in the mineral is not an essential part of the crystal lattice.

Náray-Szabó (3) is of the opinion that the effect of dehydration is so slight, due to the low water content, that no difference will be observed on the *x*-ray photographs of the natural and dehydrated material and that consequently this argument cannot be advanced in the discussion of the role of water in pollucite. Fleischer and Ksanda (9) have sought to explain the difficulties of dehydration and rehydration by virtue of the fact that "the very large caesium ion occupies much of the 'free' space in the pollucite structure. This steric effect would also account for the low water content and for the difficulty of dehydration."

Kenny, Jenny and Brown (10) have shown that particle size is an important factor determining variations in dehydration properties. In view of their results the dehydration properties in the present investigation were determined on two sieved grades of coarseness of pollucite from South West Africa. These curves are given in Fig. 3. Approximately 1.5 grams were used in each case and simultaneously heated in weighed platinum crucibles in an electric furnace for periods of 24 hours at a time, until the loss of weight, as compared with the previous weighing, did not exceed 0.03%, after which the temperature was raised another step. The crucibles were allowed to cool in a desiccator and weighed.

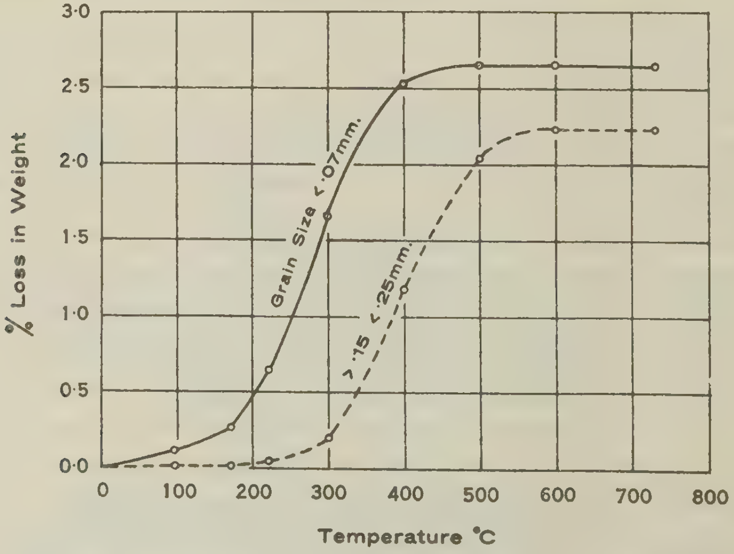

FIG. 3. Dehydration curves for pollucite from Karibib, S. W. A.

As is to be expected the pollucite of grain-size $<.07$ mm. was much more readily dehydrated than the coarser material, losing most of its water in the temperature range 200–400°C., while the coarser material lost most of its water between 300° and 500°C. It is interesting to note that whereas the pollucite of finer grain lost 2.66% the coarser material lost only 2.23% H_2O. It is thought that the thermal agitation in the latter instance is not sufficient to allow the water molecules to escape from the interior of these comparatively large grains. It would therefore seem as if grain size, among others, was an important factor which led to the different dehydration curves obtained by Strunz (2) and Fleischer and Ksanda (9). In this connection it may be of interest to mention that the dehydration curve of the Karibib pollucite of $<.07$ mm. corresponds closely to that obtained by Strunz (2) on pollucite (2.58% H_2O) from Elba.

The dehydrated pollucite of $>.15<.25$ mm. grain size shows decided though faint signs of anisotropism under the microscope. While this feature is well known in the case of dehydrated analcite, it has not yet been mentioned in connection with pollucite. The pollucite used in the past in dehydration experiments was probably too finely powdered to show any signs of anisotropism.

In both cases the dehydration curves of the pollucite from Karibib seem to indicate that the water is "bound," while the discussion in the previous section would certainly lead one to the conclusion that the water is an essential part of the crystal lattice, by virtue of the isomorphous replacement of Cs^+ by Na^+ and the concomitant introduction of a water molecule into the unit cell. This replacement results in the pollucite-analcite series which this investigation has shown to exist.

ACKNOWLEDGMENTS

In conclusion I wish to express my gratitude to my colleague, Dr. J. E. de Villiers who originally identified the pollucite, for his interest and numerous helpful suggestions; to Dr. B. Wasserstein for the qualitative spectrographic analysis and to Dr. C. F. J. van der Walt for the chemical analysis. I am indebted to the Drawing Office staff of the Geological Survey for the preparation of the text-figures.

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PROCEEDINGS OF SOCIETIES

ABSTRACTS OF MINUTES OF THE NEW YORK MINERALOGICAL CLUB

Meeting of April 19, 1944

The president, Mr. Taylor, announced the death of John A. Grenzig, an active member of the club since 1894. The officers for the following year were elected, as follows:

James A. Taylor, President
Frederick H. Pough, First Vice-President
Robert B. Sosman, Second Vice-President
Cecil H. Kindle, Treasurer
Gilman S. Stanton and John N. Trainer, Directors
Elizabeth Armstrong, Secretary

Dr. Michael Fleischer of the United States Geological Survey spoke on "The Mineralogy of the Manganese Oxides," reviewing the various oxides and the identification techniques necessary for distinguishing them.

Meeting of May 17, 1944

The officers gave their annual reports and a club trip to the William Boyce Thompson collection was planned. The president, Mr. Taylor, announced the death of William H. McClelland. The speaker of the evening, Dr. Frederick H. Pough, reported on some of the mineralogical highlights of his recent trip to South America.

Elizabeth Armstrong, *Secretary.*

BOOK REVIEWS

THE SYSTEM OF MINERALOGY OF JAMES DWIGHT DANA AND EDWARD SALISBURY DANA, Yale University, 1837–1892, seventh edition, entirely rewritten and greatly enlarged, by Charles Palache, Harry Berman, and Clifford Frondel, Harvard University; volume I, elements, sulfides, sulfosalts, oxides. New York (John Wiley & Sons), London (Chapman & Hall) 1944, xi+834 pages, many figures. $6\frac{1}{4}\times 9\frac{1}{4}$ inches. Price $10.00.

To most of us *Dana's System* has always meant the *Descriptive Mineralogy* of E. S. Dana (1892), which proved so complete and accurate and judicious a compilation that it gained something of the authority and even the finality of Holy Writ. But this *Dana* was the sixth version of a work by J. D. Dana, originally published in 1837 and five times revised, sometimes with radical changes, in the ensuing period of five and fifty years. A comparison of the first edition with the sixth shows how greatly mineralogy developed in the intervening years, and the rows of volumes that have been added to the journals of mineralogy since 1892 show that there has been no abatement, rather an increase, in the rate of this development in the last half century.

The authors of the first volume of the new *Dana* were thus faced with the huge task of covering at a single stride at least as much as the Dana's did in five. At the outset they decided that the general form of the new work should follow that of the last *System*. The conception of a mineral species remains essentially unchanged, and the description of a species follows the traditional general order: crystallography, physical properties, chemical properties, occurrences.

But in detail we find many differences from the old system. Dana's inflexible system of species numbers, which gave the impression of finality, are replaced by an elastic system of numbers, usually four integers, such as 2613, meaning Class 2 (Sulfides), Type 6 (AX), Group 1 (Galena Group), Species 3 (Altaite). The specific name is followed by a revised and extended synonymy. The thoroughly revised geometrical crystallography is presented in a form designed to meet the needs of two-circle and single-circle goniometry. Improved angular values, supported by many new measurements, from the Harvard Laboratory and from the notebooks of the late Henri Ungemach, are frequently combined with new settings conforming to x-ray results, to give new geometrical elements and calculated angles. The many excellent crystal drawings are new or redrawn, if necessary in new positions. X-ray results are limited to the space-group of the atomic structure (in Hermann-Mauguin notation), the absolute and relative dimensions of the unit cell (to compare with the geometrical elements), and its atomic content (to compare with the simplest mineral composition).

The physical properties include many improved measurements of specific gravity (made with Berman's serviceable micro-balance), and the principal optical properties of opaque minerals in polished sections. The optical properties of non-opaque minerals are given in a separate section, using X, Y, Z, O, E, for vibration directions and n for refractive index, dispensing with α, β, γ, ω, ϵ, and employing r and v instead of ρ and υ for axial dispersion. The chemical properties include the chemical formula written in the form $A_mB_n \cdots$, the calculated composition, selected analyses, and notes on the chemical varieties, using Schaller's chemical qualifiers with the name of the species (*mercurian silver*) in place of varietal names (*arquerite*), and thus relegating many varietal names to the synonymy. The notes on selected occurrences often include remarks on the probable mode of origin. The authorities for all the important observations are given in the reference section, with supplementary data, lists of rare and uncertain forms, transformation formulae, and remarks on problematical matters.

In modifying the mineral classification to suit the needs of modern crystal chemistry Dana's classes (elements, sulfides, . . .) are essentially retained while substantial changes are introduced in the subdivision of the classes into chemical types (A_mX_p or $A_mB_nX_p$), series of minerals with serial properties, or groups of more or less related species. Within each class the types are arranged in order of decreasing $m:p$ or $(m+n):p$, that is in decreasing ratio of metallic to non-metallic elements; and thus the system commences with gold rather than with diamond. As in the old *Dana* the authors' decisions on the validity of mineral names can be inferred from the typography, in which, in a general way, four degrees can be discerned: established species of complete individuality; minerals which for some reason fall short of full-rank species; ill-defined and doubtful substances; and discredited names and synonyms.

These are but some of the changes that appear in the new *System*; others will be apparent when studying the introduction and the specific descriptions, where extensive changes and additions will be found. Without question every mineralogist will welcome the appearance of the first volume of the new work, in which he will find a critical appraisal, selection, and arrangement of factual mineralogy backed by the leading school in the United States. Those engaged in intensive mineralogical work will also turn to the references for direct leads to the more important sources. In this connection it should be mentioned that, although references as late as 1943 are included, unusual difficulties and delays in preparing and publishing the work appear to have led to the occasional omission or insufficient consideration of still earlier results; these can be quickly found in the recent volumes of *Mineralogical Abstracts*.

It would be surprising if a work which endeavors to bridge so large a gap at a difficult time, both in the development of mineralogy and in world affairs, did not show some signs of these disturbing influences and evoke some criticism or dissent on one score or another. Here we shall leave such matters aside and join the mineralogical profession in offering to Emeritus Professor Palache and his associates the warmest congratulations in bringing the first volume of their great work to completion, and expressing the hope that the succeeding volumes on the mineral salts and silicates will follow in the not too distant future.

In conclusion we refer with great regret to the accidental death of Harry Berman, which was reported shortly after the announcement of the publication of the work to which he had devoted himself and would have carried on to completion.

M. A. PEACOCK,
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PHOTOMICROGRAPHY IN THEORY AND PRACTICE, by CHARLES PATTEN SHILLABER. New York, John Wiley and Sons (1944). Pp. vii+773; figs. 291. Price $10.00.

The subject matter of this book is divided into eight chapters, with each chapter subdivided into sections for ready cross reference.

Chapter 1 discusses the mechanics of the microscope in a complete and understandable manner. All types of modern research and petrographic microscopes are described and illustrated.

Chapter 2 covers the large range of methods of lighting used with the microscope, together with photometric and other lamp data.

Chapter 3, extending over 137 pages, is devoted to a discussion of light waves and optical paths through various media and through a simple lens. This is followed by a detailed description and evaluation of microscope objectives together with their care and cleaning.

Chapter 4 deals with oculars and condensers. Dark-field methods are briefly explained for use with biological specimens and for photographing crystals. Also described are the correct condensers used in ultraviolet work and for demonstrating fluorescence.

Chapter 5 takes up the subject of optical filters with a discussion of their selection, use and care. The control of glare from the microscope and outside sources is extensively dealt with.

Chapter 6 is devoted to the camera and also to photosensitive materials and formulae. Simple vertical cameras as well as the larger and more expensive horizontal types are illustrated and briefly described. Comparison illustrations are used to show the effect of formulae on graininess in the film.

Chapter 7 deals with use and application in photography of various mounting media, stains, reagents and solvents. A 14 page table is provided giving the composition and use of some important etching agents used in metallography.

Chapter 8 presents in 47 pages, an analysis of practical photomicrographical problems. Many illustrations are used to show what may be accomplished in photographing difficult materials.

A glossary of optical terms used in Microscopy is appended. The index is very well organized.

The author states that the material is basic and that the book is largely a book of reference. The mineralogists who employ photography will find this book a valuable aid, written in a concise but complete style. Research workers and students who desire to improve their methods of making photomicrographs will find here a very stimulating book to add to their library.

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NEW MINERAL NAMES

Eckermannite

OLGE J. ADAMSON, Eckermannite, a new alkali amphibole: *Geol. För. Förh.*, **64**, 329–334 (1942); through *Chem. Zentr.* **1943**, I, 2078.

CHEMICAL PROPERTIES: Analysis gave SiO_2 56.45, TiO_2 0.39, Al_2O_3 5.47, Fe_2O_3 9.49, FeO 1.90, MnO 0.52, ZnO 0.67, MgO 9.43, CaO 0.35, Na_2O 11.30, K_2O 2.41, H_2O 0.33, F 2.69; sum 101.30−(O=F_2) 1.09=100.21%. This corresponds to $Na_4Mg_2AlFe(Si_4O_{11})_2(O, OH, F)_2$.

Physical and Optical Properties: The mineral is optically negative, n_{Na} (all ±.003), $\alpha=1.636$ (bluish-green), $\beta=1.644$ (bright bluish-green), $\gamma=1.649$ (pale yellowish-green), 2V about 74°. Extinction $X\wedge c=25°$. G. = 3.16.

Occurrence: The mineral occurs in alkalic rocks of the Norra Kärr region, southern Sweden, associated with feldspar, pectolite, aegirine, apatite, sphene and altered nepheline.

Michael Fleischer.

Formanite

Harry Berman and Clifford Frondel, *Dana's System of Mineralogy*, 7th Ed., Vol. **1**, pp. 757–763.

Name: For Francis Gloster Forman, government geologist of Western Australia.

This name is given to the $YTaO_4$ end member of the fergusonite series. Material from Cooglegong, W. Australia, close to the end member in composition was analyzed by Simpson, *Proc. Australasian Assoc. Adv. Sci.*, **2**, 310 (1909). Other analyses show gradations to fergusonite, $YCbO_4$. Y is replaced in part by U, Th, Ce, Ca; Ta and Cb in part by Ti.

M.F.

Neodigenite

Paul Ramdohr, The minerals in the system Cu_2S–CuS: *Zeit. prakt. Geol.* **51**, 1–9 (1934); through *Chem. Zentr.*, 1943, I, 2387-2388; through *Chem. Abstracts*, **38**, 4500–4501 (1944).

This name is given to cubic Cu_9S_5. The original paper is not available and the abstract gives no reasons why the new name is to be preferred to the name digenite.

M.F.

DISCREDITED MINERALS

Katangite (= Chrysocolla)

V. Billiet, The relations of chrysocolla, katangite, plancheite, bisbeeite, shattuckite and dioptase: *Verh. Kon. Vlaamsche Acad. Wetensch., Letteren schoone Kunsten België, Klasse Wetensch.*, **4**, No. 1, 58 pp. (1942); through *Chem. Zentr.*, **1943**, II, 13.

X-ray powder diffraction data indicate that dioptase ($CuSiO_3\cdot H_2O$), shattuckite ($2CuSiO_3\cdot H_2O$), plancheite ($3CuSiO_3\cdot H_2O$) and chrysocolla ($CuSiO_3\cdot 2H_2O$) are independent species. Katangite (see *Am. Mineral.*, **8**, 39) is a variety of chrysocolla. The status of bisbeeite is uncertain.

M. F.

Treanorite (= Allanite)

A. O. Woodford, Crestmore minerals: *Cal. Jour. Mines and Geology*, **39**, No. 3, 333–365 (1943). (Published in 1944.)

New data are given for treanorite, first described in *Am. Mineral.*, **26**, 351 (1941). Analysis by R. B. Ellestad gave SiO_2 34.30, Al_2O_3 22.18, Fe_2O_3 5.83, FeO 5.98, MgO 0.48, CaO 16.81, H_2O+1.46, H_2O-0.04, TiO_2 0.19, Ce_2O_3 5.81, $(La, etc.)_2O_3$ 7.05; sum 100.13%. Other samples contained more, but most contained less rare earths. The molecular ratios do not lead easily to a simple and satisfactory formula. The optical properties are variable; the analyzed material had α about 1.749, $\beta=1.7525$, $\gamma=1.766+$. It is concluded by Woodford that treanorite must be considered a synonym of allanite, although further work may show it to be a new mineral.

Discussion: Recalculation of the analysis leads to the ratios (Ca, Ce, La):Al, Fe^{III}, Fe^{II}, Mg):Si = 1.95:3.12:2.95, in fairly good agreement with the allanite formula.

M.F.

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